A DENDROCLIMATIC STUDY OF *LIBOCEDRUS BIDWILLII* HOOK. F. (KAIKAWAKA)

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Limin Xiong

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This thesis demonstrates some of the potential of *Libocedrus bidwillii* Hook. f. (Kaikawaka) for dendroclimatological research by developing tree-ring chronologies and then using these chronologies to reconstruct palaeoclimates.

In order to assist with the modelling of tree-growth and climate relationships (response function analysis), the annual nature of *Libocedrus bidwillii* growth was investigated. Results showed that seedlings of *Libocedrus bidwillii* were sensitive to temperature and soil moisture. Greatest growth was at high soil moisture and under a variable temperature regime. It was also found that there was an obvious seasonal variation in the growth of the seedlings. Such information allowed some confidence in the use of the species as a proxy-climatic indicator.

Twenty-three tree-ring chronologies were developed from different areas of New Zealand. These included 12 new sites, 5 sites collected by other people but then updated and 6 sites that were not updated.

Standardisation of the tree-ring series from each site used double detrending methods - ERH+SP67% (linear-Exponential or linear Regression or a Horizontal detrending plus SPline detrending fitted to 2/3 the length of the tree-ring series). This meant some long-term trends in the data were retained (i. e. greater than 120 year cycles) although this led to some reduction of the strength of the common signal in the chronology as measured by EPS (Expressed Population Signal) and SNR (Signal of Noise Ratio). The retention of long-term trends in the chronologies was thought to

be important because some low frequency signals, which are longer than 120 years, are present in the climate data.

Autocorrelation in the chronologies was removed by the ARSTAN program using the Aikaike Information Criterion (AIC) to determine the filter model. No significant autocorrelations were left in the residual chronologies produced by this method.

Inter-comparison of the chronologies showed a highly consistent and significant pattern between most of the sites. There was little reduction in inter-chronology correlation with separation distance. However, there was a difference, or an effect, due to altitude.

In general the response functions for the relationship between climate variables and ring-width in any given growing season showed a negative relationship between temperature for the prior growth months February, March and current December, while there was a positive response to temperature in September and February. There were three significant negative coefficients (previous March, April and August) and one positive (current February) for precipitation.

The results of using principal component analysis (PCA) showed that all the 27 significant response function analyses could be divided into four groups. The response pattern in the four groups was similar for temperature but the rainfall response was more variable.

The climate reconstructions were based on two groups of chronologies: eleven chronologies from all over New Zealand and a subset of only the three longest chronologies. Comparison of the climate data of different seasons with the two groups of chronologies was carried out using the "bootstrap" transfer function. The average February-March temperature and total March-April precipitation were finally selected as the reconstructed variables.

Both of the groups reconstructed the hot years better than the cold years. The reconstructed temperature series were similar to all the earlier New Zealand dendroclimatic reconstructions. The warming and cooling periods, extremely warm

and extremely cold years were identified and compared with some other sources of evidence and found to be highly consistent. This led to the conclusion that *Libocedrus bidwillii* is very useful as a high resolution palaeotemperature indicator.

In the precipitation reconstruction, all the periodicities (both high and low) in the observed data were reconstructed. The dry and wet periods, severe drought and very wet years were identified in both precipitation reconstructions and also compared with other more limited sources of evidence.

Keywords: *Libocedrus bidwillii*; dendroclimatology; palaeoclimatology; dendrochronology; tree-rings; New Zealand climate reconstruction.

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INTRODUCTION

1.1 The importance of proxy-data in climate research

The understanding of global climate systems has become an increasingly important goal of scientific research in a world facing an expanding population and increasing pressure on the environment and resources. The growing awareness of the problem of climatic variability and its impact on human affairs is shown by the wide series of recent publications including newspaper articles. Consequently, there is a pressing demand for estimates of climatic change. In order to gain some understanding of climatic variation on time scales greater than a few decades, proxy climate records are needed since instrumental records are limited or do not exist.

Continuous records of surface elements such as atmospheric pressure, temperature and precipitation only go back a few hundred years at most. Compared to the instrumental and historical climate records of the Northern Hemisphere (Lamb, 1977), the Southern Hemisphere has relatively few high-resolution climatic time series that extend back more than 100 years (Barry, 1978). Fortunately, information about climate before the beginning of instrumental observations can be obtained from the study of a variety of physical and biological phenomena that respond to climate. The annual rings of trees are one of the most valuable sources of climatic proxy data (Hughes *et al.* 1982). Trees grow in most land areas of the Earth, they can reach ages of several hundred to a few thousand years, and under favourable circumstances their growth rings can be dated to the exact year of formation. More important is the potential for detailed palaeoclimatic reconstructions because the physical and chemical properties of the annual rings can produce records of a broad range of environmental variables that are directly (or indirectly) linked to climate.

The development of an archive of well-dated baseline tree-ring information will provide valuable information before human-induced change becomes pervasive. The information in such a data base could provide the only long term record for New Zealand. Such information may be critical for evaluating anthropogenically induced climate change, its magnitude and extent as well as for reconstructing past climates, especially since meteorological records in New Zealand only commenced in AD 1850.

1.2 Dendrochronological and dendroclimatological research

1.2.1 Introduction

The study of the annual growth of trees and the consequent assembling of long, continuous chronologies for use in dating wood is called dendrochronology. The study of the relationships between annual tree growth and climate is called dendroclimatology (Briffa, 1984).

Since the pioneering work of Douglas (1919) in the south-western United States, the science of dendrochronology has been used in different studies of climate, ecology, hydrology, and geomorphology in many parts of the world. Most of the work has been done in Northern American and Europe (Fritts, 1976; Hughes *et al.* 1982; Schweingruber, 1983; Cook *et al.* 1990; Fritts, 1991). Recently such work has also been done in the Southern Hemisphere (LaMarche *et al*, 1979a, 1979b; Dunwiddie, 1979; Norton, 1983a, 1983b, 1983c; Palmer, 1989; Cook *et al.* 1991, 1992; Salinger *et al.* 1994).

A thorough review of the background and concepts of dendroclimatology, including many aspects of tree physiology, statistics and reconstruction methodology, can be found in Fritts (1976). This also gives many references to earlier publications. The most recent summaries that provide an updated coverage of principles, concepts, and methods of tree-ring analysis around the world can be found in Hughes *et al.* (1982), Cook *et al.* (1990) and Fritts (1991). In recent years, the ITRDB (International

Tree-Ring Data Bank) has also been established (Webb, 1993). Researchers from around the world can easily contribute and use the data in the data bank.

1.2.2 Dendrochronological study in Australia and New Zealand

General reviews of the use of dendroclimatic techniques in Australia and New Zealand are given by Bell (1958), Bell & Bell (1958), Ogden (1978, 1981, 1982), Dunwiddie & LaMarche (1980), Norton & Ogden (1987), Palmer (1989), Norton (1990) and Norton & Palmer (1992).

The predominant Australian tree genus, *Eucalyptus*, has shown little promise for dendrochronology (Ogden, 1978), although limited cross-dating has been achieved between subalpine *E. pauciflora* trees (Ogden, 1982). The only chronology developed from an Australian angiosperm is *Nothofagus gunnii* from Tasmania. More success has been achieved with conifers. Two chronologies have been developed from *Callitris robusta*, they are only 43 and 64 years long because of the general young age of the trees. Four chronologies have been published with the Tasmanian *Arthrotaxis cupressoides* and *A. selaginoides*. One of the *A. cupressoides* chronologies covers the period 1028-1974. Ten chronologies have also been developed for *Phyllocladus asplenifolius* (LaMarche *et al.* 1979b). The longest published chronology was developed from *Lagarostrobus franklinii* in Tasmania which covered from AD 900 to AD 1988 (Cook *et al.* 1991) (Table 1.1).

In New Zealand, early dendrochronological research was largely unsuccessful, and a pessimistic attitude developed toward this technique (Bell, 1958; Bell and Bell, 1958; Cameron, 1960; Scot, 1964, 1972; Wardle, 1963b; Franklin, 1969; Wells, 1972). For example, Hutchinson (1926) made the first observations on tree rings in native species regarding mensuration studies. Oliver(1931) and Lockerbie (1950) estimated ages of Maori archaeological sites based on growth rates of trees growing on top of the sites. Using ring counts, Batley (1956) estimated dates of scarring on *Podocarpus totara* trunks by the Maoris, and Cameron (1960) made ring counts on *Dacrydium cupressinum* in a study of past lake levels. However, since the mid

Table 1.1 Synopsis of Australia and New Zealand tree-ring chronologies (After Palmer, 1989; Norton & Palmer, 1992)

Species	No.	Lat.	Alt.	Leng.	AC	MS	R
Australia							
Arthrotaxis cupressoides[1]	3	41°45'-42°41'	1200	699	.65	.13	.38
A. selaginoides[1]	1	41°38'	1000	778	.62	.14	.27
Callitris robusta[1]	2	32°00'-32°07'	4-15	54	.06	.21	.40
Lagarostrobus franklinii[2]	1	41°50' (about)	950	1089	N.A.	N.A.	N.A.
Nothofagus gunnii[1]	1	41°38'	1000	244	.52	.17	.40
Phyllocladus aspleniifolius[1]	10	41°11'-43°28'	200-900	388	.26	.29	.36
New Zealand							
Agathis australis[*,3,4,5]	12	35°11'-37°36'	75-468	316	.31	.26	.31
Halocarpus biformis[3]	1	45°32'	305	410	.75	.10	.15
Lagarostrobos colensoi[3]	2	39°21'-42°23'	244-1000	543	.62	.13	.17
Libocedrus bidwillii[3,6]	11	39°15'-46°23'	244-1067	459	.68	.15	.30
Nothofagus menziesii[6]	5	43°03'-45°18'	950-1275	347	.42	.31	.35
N. solandri[6]	25	43°01'-45°18'	610-1400	222	.50	.31	.42
Phyllocladus alpinus[3]	1	42°54'	915	260	.57	.13	.19
P. glaucus[3,7]	5	37°30'-38°42'	520-1000	291	-.36	.44	.46
P. trichomanoides[*,3,7]	10	38°18'-41°07'	15-640	289	.13	.26	.33

Note: No. number of published chronologies.
Lat. latitudinal range of chronologies.
Alt. altitudinal range of chronologies in metres.
Leng. average chronology length (year).
AC average lag-one autocorrelation.
MS average mean sensitivity.
N.A.: Not available.
R average mean correlation between all radii in chronology.
* subfossil chronologies are not included.
1 LaMarche *et al.* 1979b
2 Cook *et al.* 1991
3 LaMarche *et al.* 1979a
4 Ahmed 1984; Ahmed & Ogden 1985
5 Palmer 1982
6 Norton 1983a,b,c
7 Palmer 1989

1970's, modern dendrochronological techniques have been successfully applied to mesic forest trees in New Zealand. Initial sampling in New Zealand concentrated on seven coniferous species with 21 chronologies produced (LaMarche et al, 1979a; Dunwiddie, 1979). Additional chronologies have been developed subsequently for *Agathis australis* (Palmer, 1982; Ahmed 1984; Ahmed & Ogden 1985), *Nothofagus* *solandri* and *N. menziesii* (Norton 1983b,c) and *Phyllocladus trichomanoides* and *P. glaucus* (Palmer 1989). Up to 1992, 72 modern, 2 subfossil chronologies had been produced from 9 species (Norton & Ogden, 1987; Norton & Palmer, 1992). Several of these conifer chronologies extend back before AD 1500 (Table 1.1).

1.2.3 Dendroclimatic reconstructions in Australia and New Zealand

The published Australian palaeoclimate reconstructions based on tree-rings all come from Tasmania and a summary is given in Table 1.2. For New Zealand, three temperature, one precipitation, one river-flow, one zonal and meridional flow have so far been developed (Table 1.2). The following sections review the reconstructions in more detail.

A) Tasmanian temperature

As mentioned above, the temperature reconstructions published for Australia were all based on chronologies from Tasmania (LaMarche & Pittock, 1982; Cook *et al.* 1992). LaMarche & Pittock's (1982) reconstructions were based on a grid of 11 tree-ring chronologies. The data set included three genera (*Arthrotaxis*, *Phyllocladus* and *Nothofagus*) and three composite chronologies (obtained by averaging two or more individual chronologies together). The chronologies were developed using a mixture of standardisation techniques (LaMarche *et al.* 1979b). The eleven tree-ring chronologies together with data from 15 climate stations were subjected to principal component analysis, then a step-wise canonical regression (Fritts *et al.* 1979) to derive a transfer function for reconstructing past climates. From this transfer function, estimates of yearly values of October-May temperature were made for each of the 15 climate stations. Three stations were verified (Waratah, Cape Sorell and Cape Bruny; Table 1.2) with adequate temperature records. The reconstructions were interpreted as showing periods of above average temperatures between the early 1830s and the late 1850s, and the late 1890s to the mid-1910s. Cooler periods occurred during the mid-1810s to early 1830s, and the late 1850s to late 1870s. The reconstruction made by Cook *et al.* (1992) was based on a 1089-year tree-ring chronology of Huon Pine (*Lagarostrobus franklinii*) at 950m elevation on Mount Read located in western Tasmania. The long-term mean of this reconstructed November-April temperature since AD 900 is 14.99°C with a standard deviation of ±0.397°C. Eight warmest and coldest 25-year periods in the temperature reconstruction were given (Cook *et al.* 1992).

B) Tasmanian stream-flow

Reconstructions of stream-flow for eight rivers in western Tasmania were developed (Campbell, 1982) using the same grid of 11 tree-ring chronologies described in the above (Table 1.2). Transfer functions were developed using the canonical regression procedure and were calculated over a 16 year period (1958-1973) common to all stream-flow records. Verification was only possible for three of the stream-flow records. The results do suggest some ability to reconstruct stream-flow in the tree-ring data set and examination of the one reconstruction presented indicates periods of higher than average flow from about 1790-1820 and 1890-1930, and below average flow since the 1930s.

C) New Zealand temperature (*Nothofagus*)

The first temperature series from tree rings was based on a South Island network of *Nothofagus* species chronologies (Norton *et al.*, 1989). Temperature records from seven New Zealand stations have been used to develop a regional NZ temperature series back to 1853 (Salinger, 1980). The summer component (December to March) was used in developing the temperature reconstruction. The tree-ring data were standardised using the 60-year Gaussian filter method (Briffa, 1984). A principal components regression technique (Briffa *et al.* 1983, 1986) was used to relate the tree-ring chronologies with the temperature data. The temperature data set was divided into two equal periods for analysis, 1853-1915 and 1916-1979, with two regressions being developed for each period and verified on the other period. The reconstruction was then taken back to 1730. The results of variance spectra calculated over the reconstructed and recorded data series indicate that periodicities in the data up to about 30 years in length are reliably constructed. They also suggest that the reliability may be even greater at higher frequencies. Low common variance above cycles of 40 years is a consequence of the standardisation technique used in this reconstruction. The reconstruction was interpreted as showing that cooler summers were more common in the mid-1730s, 1760s, 1780s, and mid-1840s, while warmer summers appeared to have been more common in the early-1730s, 1750s, 1770s, mid-1790s, 1805-1815, and the 1830s.

D) New Zealand temperature (*Phyllocladus*)

Seven chronologies derived from *Phyllocladus trichomanoides* and two from *P. glaucus* in the central North Island were used in the January-March temperature reconstruction (Palmer, 1989). Transfer functions were developed using the principal components regression method described above which reconstructed summer temperature back to 1750. Results of the two regressions and their verifications are presented in Table 1.2. Cross-spectral analysis was used to assess how well the estimated summer temperatures portrayed the high and low frequency variation shown in the instrumental data over the common period (1853-1982). As expected (from standardising with a 50 year Gaussian filter) the reconstructed series best modelled the high frequency variation. However, no periodicities occurred in the reconstructed series that were not already present in the observed summer temperature data. Interpretation of the reconstructed temperature data was cautious because of the relatively low amount of variance explained in calibrating the transfer function models. However, the similarity between the *Phyllocladus* reconstruction and that developed by Norton *et al.* (1989) with *Nothofagus* was considered encouraging.

E) New Zealand temperature (mixed species)

The reconstructions made use of eight ring-width chronologies from five endemic species (three different genera, *Agathis, Phyllocladus, Nothofagus*); the first time multi-species reconstructions had been attempted in New Zealand (Salinger *et al.*

1994). The chronologies were standardised using cubic splines to remove variance on time-scales longer than two-thirds the length of each tree series (Cook and Briffa, 1990). Average November to March temperature from NZ average temperature series (Salinger, 1980) was used in the transfer function. The principal component regression technique described by Briffa *et al.* (1983, 1986) was used. The calibration and verification statistics for the regressions over the two periods (Table 1.2) are similar. The two regression equations were then applied to the tree-ring data set to reconstruct past temperature back to 1731. The comparisons of each of the two summer temperature reconstructions with those above two reconstructions showed a very high significance (Salinger *et al.* 1994). This clearly demonstrated the potential for multi-species inclusion to form a much greater network of chronologies since one of the major limitations is the spatial distribution pattern of single species (*e.g. Agathis australis; Phyllocladus glaucus; P. trichomanoides* and *Nothofagus*).

F) Canterbury precipitation and stream-flow

Four *Nothofagus solandri* tree-ring chronologies developed from trees growing at mid-altitude sites in Canterbury, on the east coast of South Island were used to develop reconstructions of precipitation and stream-flow (Norton, 1987). Chronology development used the same Gaussian filter standardisation method described in earlier section C. The growing season (November-January) precipitation data from Lake Coleridge, and stream-flow data from the Hurunui River were used. Statistics describing of the two regressions are presented in Table 1.2. Although the precipitation reconstruction is too short to identify any obvious trends with time (only back to 1879), the stream-flow reconstruction shows a greater frequency and intensity of low flow events prior to the observed data.

G) New Zealand zonal and meridional flow (mixed species)

The same group of chronologies as described in section E were used to reconstruct the seasonal (November to March) zonal and meridional pressure gradient across

Table 1.2 Summary of Australia and New Zealand climate reconstruction models (After Palmer, 1989; Norton & Palmer, 1992)

Records	Type	Calibration		Verification		
		Period	%var	Period	%var	RE
Australia						
Waratah[1]	T	1941-1968	81.0	1899-1940	39.7	0.12
Cape Sorell[1]		1941-1969	77.4	1900-1940	18.5	-0.58
Cape Bruny[1]		1941-1969	54.8	1924-1940	31.4	0.04
Mount Read[2]		1938-1989	0.607*	1887-1937	0.471*	0.101
Station 40[3]	F	1958-1973	36.0	1922-1933 & 1951-1957	49.0	0.40
Station 46[3]		1958-1973	59.3	-	-	-
Station 78[3]		1958-1973	51.8	1924-1957	9.0	-0.38
Station 119[3]		1958-1973	68.9	1949-1957	32.5	0.11
Station 154[3]		1958-1973	53.3	-	-	-
Station 159[3]		1958-1973	27.0	-	-	-
Station 183[3]		1958-1973	59.3	-	-	-
Record 10087[3]		1958-1973	60.8	-	-	-
New Zealand						
Nothofagus (early)[4]	T	1853-1915	65.6	1916-1979	33.6	-0.13
Nothofagus (late)[4]		1916-1979	54.8	1853-1915	42.3	0.06
Phyllocladus (early)[5]		1853-1917	46.9	1918-1982	24.6	0.14
Phyllocladus (late)[5]		1918-1982	32.0	1853-1917	32.1	0.28
Mixed species (early)[6]		1863-1920	55.0	1921-1976	30.0	0.14
Mixed species (late)[6]		1921-1976	49.0	1863-1920	33.0	0.10
Coleridge[7]	R	1913-1962	46.2	1963-1977	57.8	0.56
Hurunui[7]	F	1956-1977	51.8	-	-	-
Mixed species (early)[6]	ZP	1911-1940	37.0	1941-1976	18.0	0.19
Mixed species (late)[6]		1941-1976	33.0	1911-1940	22.0	0.22
Mixed species (early)[6]	MP	1931-1954	43.0	1955-1976	28.0	0.12
Mixed species (late)[6]		1955-1976	31.0	1931-1954	39.0	0.28

Note: * Pearson product-moment correlation coefficient.

%var: % variance explained. RE: reduction of error variance.
T. temperature. R: rainfall.
F: riverflow. ZP: zonal pressure.
MP: meridional pressure. 1 LaMarche & Pittock, 1982.
2 Cook *et al.*, 1992. 3 Campbell, 1982.
4 Norton *et al.*, 1989. 5 Palmer, 1989.
6 Salinger *et al.*, 1994. 7 Norton, 1987.

New Zealand for the period 1731-1976 (Salinger *et al.* 1994). Mean sea-level pressure for Auckland, Christchurch, Chatham Island, and Hobart (Tasmania) were used to derive pressure gradients of zonal and meridional flow in the New Zealand region. The measure of zonal flow across New Zealand was represented by the Auckland minus Christchurch pressure gradient. The Hobart minus Chatham Island pressure gradient measured meridional flow.

The calibration and verification statistics for the two periods in the zonal flow reconstruction are similar (Table 1.2). Although the calibration periods were short (30 years), both showed the trend to a weaker zonal circulation across New Zealand in the 1970s. The two reconstructions showed alternating periods of weaker and more intense zonal circulation affecting New Zealand. From 1730 westerly flow increases up until 1770. This is followed by a weakening with a distinct minimum in the 1830s. The Auckland-Christchurch pressure gradient then increased rapidly to reach a maximum during the 1840s and 1850s. Zonal flow subsequently gradually weakened to another minimum in the 1910s, after which there was another rapid increase in the 1920s. The early-calibrated meridional reconstruction had about double the amplitude in the reconstructed series than the late-calibrated reconstruction. In the latter reconstruction there was no apparent trend in the data. Both reconstructions suggested high interannual variability in meridional flow. The early reconstruction suggested that slightly more southerly airflow occurred in the first half of the 1800s, and that this decreased to a minimum in the 1880s. Southerly flow then increases to a maximum between 1900 and 1915, and decreased subsequently (with oscillations). No secular trends were apparent in the late reconstruction.

1.3 Review of *Libocedrus bidwillii* research

1.3.1 Introduction

Libocedrus bidwillii is widely distributed throughout New Zealand. This wide geographical spread (both in altitude and latitude) made the species highly suitable for dendroclimatic research. Other features of the species which indicated its strong suitability for dendrochronological study were: the fact that the annual-rings are clear, very old ages are attained (e.g. > 500 years) and there was large year to year variation in ring size (i.e. indicates possible 'sensitivity' to climate). Eleven successful chronologies had already been established, but no climate reconstructions had been attempted. The oldest chronology in New Zealand produced by this species extended to AD 1256. The important components needing to be done were (1) determine if this species was sensitive to climate not only from a statistical viewpoint, but also from a physiological viewpoint; (2) extend both spatially and temporally the network of chronology sites as far as possible. This would provide a better basis for climate reconstructions.

1.3.2 Distribution and habitat

Libocedrus is a genus of *Cupressaceae*. The genus has 9 species. It is distributed in California, Chile, China, Japan, New Caledonia, New Guinea and New Zealand. The genus is the only representative of the *Cupressaceae* in New Zealand. Two species are found in New Zealand - *L. plumosa* and *L. bidwillii*. *Libocedrus bidwillii* is a prominent conifer species in New Zealand's evergreen conifer-broadleaved hardwood forests in the montane-subalpine zone (Poole & Adams, 1986).

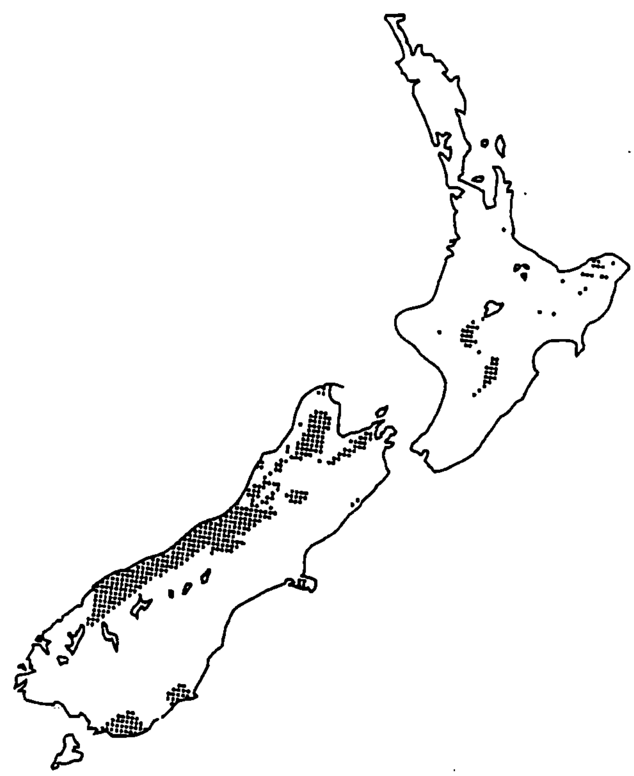


Figure 1.1 The natural distribution of *Libocedrus bidwillii* in New Zealand (Clifton, 1990)

Libocedrus bidwillii is found in both islands of New Zealand as a canopy emergent tree in montane and sub-alpine forests, in humid and superhumid climates. High rainfall, frequent fogs, short cool summers and wet organic soils characterise the sites where it predominates (Johnson *et al.* 1977; McSaveney *et al.* 1978; Ogden & Stewart, 1995). It occurs in the North Island southwards from 36°50'S mainly in montane and subalpine forests from 500 - 1300m elevation and in the South Island as far south as 46°30'S but in lowland as well as montane and subalpine forests from near sea-level to 1200 m (Figure 1.1) (Hinds & Reid, 1957).

1.3.3 Autecology

A) Growth form

Libocedrus bidwillii trees can often exceed 30 m in height and 80 cm in diameter (Veblen & Stewart, 1981). The maximum recorded age of *Libocedrus bidwillii* is 720 years (Dunwiddie, 1979). The tree often forms a typical conifer tapered conical shape and has an unmistakable papery bark.

B) Growth rates

Table 1.3 Diameter increments of *Libocedrus bidwillii*

Source	Belt	Increment (mm/year)	Community
Wardle, 1963a	CT-S	0.5-1.4	Conifer/broadleaved
Wardle, 1978	CT	2.6	Young trees on alluvial terrace
Wardle, 1978	S	1.2	Conifer/broadleaved
Wardle, 1978	S	0.8	Severe sites

Note: CT = Cool-temperate; S = Subalpine

Reported growth rates using healthy adult trees were derived from annual shoot extension measurements and from the number of annual growth rings in stems (Dunwiddie, 1979; Wardle, 1991). The table (Table 1.3) indicates that the species was relatively slow growing compared with other species. For example, the diameter increment of *Agathis australis* was from 2.3-8.2 mm/year. *Dacrydium cupressinum* was from 0.9-8.1 mm/year. *Nothofagus* species were 10-20 mm/year. *Phyllocladus trichomanoides* was 2.6 mm/year (Wardle, 1991). Compared with the mean annual growth ring widths of other gymnosperms and angiosperms species in New Zealand (Ogden & Stewart, 1995), *Libocedrus bidwillii* grew slowly.

C) Nature of apical buds

In most trees and shrubs native to the northern temperate zone, the overwintering apical buds are sheathed by special protective structures and therefore present an appearance very different from that of the apices of actively growing shoots. However, in many woody species of the New Zealand mountains the apical buds are protected only by developing foliage leaves. These two sorts of buds are referred to as specialised and unspecialised respectively. *Libocedrus bidwillii*'s apical buds are unspecialised, and shoots with bud scale or bud scar regions distinguishable only by examination of internal growth rings (Wardle, 1963a).

D) Freezing resistance of leaves and buds

In *Libocedrus bidwillii*, the scale-like leaves are reported to live for 6-8 years, and remain on the stem for half a dozen more (Wardle, 1991). It is also one of the few species which regularly retain their dead leaves.

Table 1.4 Winter freezing resistance of *Libocedrus bidwillii*

Leaf	Bud	Latitude	Belt	Source
-13°C	-13°C	46°30'	subalpine	Sakai & Wardle, 1978

The freezing resistance compared to many other NZ species is much lower. Wardle (1991) gave the winter freezing resistance of 58 woody species in New Zealand, *Libocedrus bidwillii* was the 10th lowest one.

E) Anatomical study

Table 1. 5 Wood characters of some New Zealand gymnosperm species (After Meylan & Butterfield, 1978)

Species (see the notes in the next page for the abbr.)			L B	A A	H B	L C	P A	P G	P T
Growth Rings	Indistinct		*	*					
	Slightly distinct		+						
	Moderately distinct		+	+	+	+			
	Distinct		+	+	+	+	+	+	+
	Very distinct						+	+	+
Ring boundary	Smooth		+	+		+	+	+	+
	Wavy				+				
Resin canals	Present								
	Absent		+	+	+	+	+	+	+
Tracheid walls	Smooth		+	+	+	+	+	+	+
	Callitrisoid thickenings								
	Helical thickenings								
	Occasionally warted		+						
Intertracheary pitting present on:	Radial walls		+	+	+	+	+	+	+
	Tangential walls	Early wood	+	+	+	+	+	+	+
		Late wood	+	+	+	+	+	+	+
		Throughout ring					+	+	+
Arrangment of intertracheary pits	Uniseriate		+	+	+	+	+	+	+
	Biseriate		+	+	+	+	+	+	+
	Multiseriate			+					
	Alternate		+	+		+	+	+	+
	Opposite		+		+	+	+	+	+
Torus	Present		+	+	+	+	+	+	+
	Absent								
Tracheid to ray pitting	Large window-like					+	+	+	+
	Large cuppressoid				+			+	+
	Small cuppressoid		+	+					
	Large taxodioid			+	*		*	*	*
	Small taxodioid		*	*					
	Piceoid								
	Pinoid								
Axial parenchyma	Absent				+	+	+	+	+
	Sparse			*					
	Abundant		+						
Rays	Nudules on end walls		+						
	Uniseriates present		+	+	+	+	+	+	+
	Part biseriates present		+	+	+		*	*	*
	Biseriate present			*					
Ray tracheids	Present								
	Absent		+	+	+	+	+	+	+

Note:
LB: *Libocedrus bidwillii* AA: *Agathis australis*
HB: *Halocarpus biformis* LC: *Lagarostrobos colensoi*
PA: *Phyllocladus alpinus* PG: *Phyllocladus glaucus*
PT: *Phyllocladus trichomanoides*
Sources of the table: *: The characters recorded by Patel (1967, 1968a, 1968b); +: Characters revealed with scanning electron microscope by Meylan & Butterfield (1978).

The wood of *Libocedrus bidwillii* is built up of tracheids, axial parenchyma cells, and uniseriate and occasionally part biseriate rays. Resin canals and ray tracheids are absent. The growth rings are slightly distinct to distinct. The intertracheary pits occur mostly on the radial walls in one and occasionally two rows per cell in an opposite or alternate arrangement. A few pits also occur on the tangential walls of the last few latewood and first few earlywood tracheids of some growth rings. The intertracheary pits in all but the last few latewood tracheids are bordered with circular pit apertures and membranes. The apertures of the pits in the latewood tracheids are sometimes slit shaped (Meylan & Butterfield, 1978). The phloem cell types of *Libocedrus bidwillii* include axial and ray parenchyma, sieve cells and fibres. Fibres are of two types: thin-walled and thick-walled. The ends of these fibres are mostly blunt or abrupt. Minute crystals (crystal sand) have been found in the radial walls of some axial parenchyma cells, sieve cells and fibres (Chan, 1985). The wood anatomical characters of some softwoods species are summarised in Table 1.5. All the species in the table have been successfully used to develop chronologies.

1.3.4 Population ecology

A) Diameter-age relations

Age and diameter of live *Libocedrus bidwillii* have been studied. Clayton-Green (1977) pointed out that there is a high correlation ($P<0.001$) between tree age and diameter, but the wide variation of age within any one size class suggests that caution is required in predicting ages from size class data and the mean age and 95% confidence limits for each 10-cm-size class show much overlapping. Stewart &

Rose (1989) thought diameter of live *Libocedrus bidwillii* could be used to predict age, particularly on gley podzol soils (the formula was: y(dbh)=0.13 × (age) - 21.24, r=0.8, p<0.001). Those growing on compound yellow-brown earth soils had faster growth rates than on the other plots, the relation was: y(dbh)=0.51 × (age) -138.77, r=0.5, p<0.01. Trees 300-400 year old on compound yellow-brow earth soils, were 40-60 cm dbh; but on gley podzol soils similar aged trees were only 10-30 cm dbh.

B) The dynamics of population

A lack of conifer seedlings, saplings, young trees and a predominance of larger and older individuals in many stands led Cockayne (1928) and later Robbins (1962) to suggest that conifer-dominated forests were a pioneer stage in the development of climax broadleaved hardwood forest. Holloway (1954a, 1964) suggested on the basis of forest distribution, composition, and regeneration pattern, that conifer regeneration failure was due to a change to a cooler and possibly drier climate during the past millennium. But several authors have found no evidence to suggest that a past climatic change in the last millennium has altered the stand age-structure of *Libocedrus bidwillii* to any detectable degree (Clayton-Greene, 1977; Norton, 1983a; Stewart & Rose, 1989; Haase, 1986). Several detailed studies of stand structures (Wardle, 1963a, 1963b, 1978; Clayton-Greene, 1977; Veblen & Stewart, 1982; Norton, 1983d; Stewart & Rose, 1989; Boase, 1988) and dendrochronology (Dunwiddie 1979; Norton, 1983a), except those of Wardle, indicate that regeneration occurs spasmodically following canopy opening as a result of windthrow or mass movement on steep slopes (Ogden & Stewart, 1995). The regeneration failure hypothesis is a consequence of accepting climax theory in which old stands would be expected to be all-aged and in equilibrium with regional climate. However, given the high frequency and magnitude of disturbances, and an active tectonic history (O'Loughlin & Owens, 1987) such stands are likely to be rare. Apparently stable and undisturbed stands may have been significantly influenced by windthrow or mass movements. The lack of small individuals in some stands is to be expected since most New Zealand conifers appear to be light demanding and would not be expected to regenerate under closed canopies in the absence of disturbance (Molloy, 1969).

Furthermore, a long-lived trees such as *Libocedrus bidwillii* (often > 700 year life span) may only require occasional seedling recruitment (Ogden & Stewart, 1995).

Veblen and Stewart (1982) demonstrated that variations in the age class structures of different stands could be accounted for by catastrophic regeneration in some cases, and gap-phase regeneration in others. Catastrophic events lead to the establishment of relatively even-aged stands, which may persist for > 700 years (Stewart & Rose, 1989) and ultimately decline without on-site replacement. On such time scales, disturbances destroying a few hectares of forest are frequent feature of the subalpine environment in New Zealand, and have been throughly documented (Grant, 1983, 1984; Clayton-Greene, 1977; Stewart & Veblen, 1982; Shaw, 1983; Allen & Wardle, 1985; Jane, 1986). Consequently, pulses of successful *Libocedrus bidwillii* regeneration can be expected to be separated in space and time, and subalpine forests containing this species comprise a mosaic of differently aged stands, in most of which recruitment will be absent (Boase, 1988). Indeed, where detailed studies have been made, some stands have been found to be totally lacking in seedlings, but others have had quite high densities of established (< 1.4m tall) seedlings.

Although young *L. bidwillii* are sometimes absent from small areas with dominant and emergent trees of the same species, its local persistence is assured when larger areas are considered. Disturbance renders sites suitable for seedling establishment or the release of already established seedlings. Various degrees of disturbance occur, from the toppling of individual trees, to widespread forest destruction by mass movements and other similar processes. The results of smaller disturbance events were more frequently observed than catastrophic disturbance influences in the present study, and may account for many of the vegetation patterns observed. These smaller-scale events such as localised windthrows, slips, debris flows, or other similar phenomena result in the death of an individual or small group of trees. Frequent clumping of trees of similar size and the occurrence of many slips of various ages and of small wind throws, are evidence of gap-phase regeneration in the subalpine forests studied. The paucity of smaller size-class stems at some sites in part reflects a lack of recent disturbance, and also the need for only occasional recruitment of seedlings of the long lived *Libocedrus bidwillii* trees to maintain populations at present levels. Disturbance is the main factor of intermittent regeneration of *L. bidwillii* in the subalpine forests investigated and has a pronounced influence on the population dynamics of these forests (Norton, 1983a).

1.3.5 Community ecology

Libocedrus bidwillii is mainly distributed in a forest community. There are in general, four kinds of indigenous forest communities in New Zealand. That is: conifer/broad-leaved forests of the lower altitudes, high-altitude conifer/broad-leaved forests, coastal forests and beech forests (Wardle, 1991).

In coastal forests and exotic forests, there is no *Libocedrus bidwillii* (Wardle, 1991).

In the conifer/broad-leaved forests of the lower altitudes, the canopy of warm-temperate mixed forests is usually at least two-tiered. Conifers, e.g. *Agathis*, *Libocedrus*, and some angiosperms, form an upper tier that may be continuous, scattered or absent; a lower tier of tall broad-leaved trees varies in density. However, *Libocedrus bidwillii* occurs in such forest only on poor soils in cold sites to the west and south of the South Island (Wardle, 1991).

In wetter areas, beech forest is often associated with *Libocedrus bidwillii.* There is evidence some of these mixed communities have arisen by the invasion of *Nothofagus* into areas otherwise dominated by *Libocedrus* (Rogers, 1989), a process which might be favoured by small-scale disturbances.

In districts lacking beech, the montane-subalpine transition is occupied by mixed forests that are short and floristically poorer than the low-altitude equivalents, and the canopy is often a dense wind-roof. Similar forest grows at the heads of some glaciated valleys that are otherwise occupied by beech forest. Scattered remnants also survive in the deforested eastern regions of the South Island. In this forest, *Libocedrus bidwillii* normally is the lower tier. Southern rata and kamahi dominate the main canopy, which is often dense and wind-smoothed. Shrubs and a ground layer *Blechnum discolor* accompanied by *Astelia nervosa* are prominent.

Table 1.6 *Libocedrus bidwillii* and main associate species in different communities (mean number of trees ≥ 30.5 cm dbh/ha)

type altitudinal range(m)	1 0-300	2 100-200	3 0-300	4 100-500	5 150-450
Dacrycarpus dacrydioides	6			5	8
Dacrydium cupressinum	8	28	11	40	1
Prumnopitys ferruginea	9	6		1	
Prumnopitys taxifolia	9				
Podocarpus hallii	9*	23	8	2	2
Lagarostrobos colensoi		8	50	26	
Libocedrus bidwillii	1	12	13	5	4
Weinmannia racemosa	64	5	2	3	
Metrosideros umbellata	37	5	4	4	
Quintinia serrata		2			
Elaeocarpus hookerianus		4			2
Griselinia littoralis	2				
Phyllocladus alpinus		6	2		
Halocarpus biformis			12	1	
Leptospermum scoparium					
Nothofagus truncata				8	
Nothofagus menziesii				6	25
Nothofagus soland var. cliff				6	62
Lepidothamnus intermedius			2	1	1

Notes:

Source: McKelvey 1984

* include *Podocarpus totara var. waihoensis*

Forest types:

1, 2, 3: Conifer/broadleaved forests; 4, 5: Podocarp/beech forests.

1. Well-drained recent alluvial sites in Westland.
2. Infertile soils on gentle terrain in Westland.
3. Poorly drained, ultra-infertile sites in Westland.
4. Sluggishly drained flat or gently sloping sites in North Westland ER.
5. poorly drained, generally flat, inland sites in North Westland.

At higher altitude communities, the predominant mountain totara (*Podocarpus hallii*) is often accompanied by *Libocedrus bidwillii*. *Hymenophyllum malingii* is usually on living or dead trunks of *Libocedrus bidwillii*, but no other vascular epiphytes are host specific (Wardle, 1991).

1.3.6 Dendrochronology

Since the mid 1970's, the dendrochronology of several species have been developed in New Zealand. *Libocedrus bidwillii* is one of the main species from which chronologies have been developed. The oldest chronology in NZ is from *Libocedrus bidwillii* extending back to AD 1256. Up to now, eleven chronologies had been established from this species by LaMarche *et al.* (1979a) and Norton (1983a).

Table 1.7 Synopsis of *Libocedrus bidwillii* tree-ring chronologies

Chronology ID	Site name	Latitude	Longitude	Altitude	No of trees/No of cores	Period (A. D.)	A. C.	M. S.	% abs rings	R
AHA189[1]	Ahaura	42°23'	171°48	244	10/32	1525-1976	0.77	0.16	0.28	0.31
ARM189[1]	Armstrong Reserve	43°50'	173°00	731	12/39	1450-1958	0.62	0.16	0.60	0.22
CRC601[2]	Cream Creek	43°05'	170°59	800	15/25	1460-1978	0.71	0.16	0.21	0.30
CRG189[1]	Mount Cargill	45°50'	170°32	576	12/38	1492-1975	0.75	0.16	0.00	0.38
EMT189[1]	Mount Egmont	39°15'	174°05	1050	12/42	1616-1975	0.50	0.16	0.03	0.27
MWO189[1]	Mangawhero R. B.	39°21'	175°29	1000	11/28	1662-1976	0.87	0.12	0.00	0.40
NET189[1]	North Egmont	39°17'	174°06	991	14/53	1625-1976	0.58	0.15	0.00	0.29
OKA189[1]	Owaka	46°23'	169°27	305	14/40	1732-1976	0.66	0.12	0.11	0.28
TKP189[1]	Takapari	40°05'	176°00	838	14/37	1256-1976	0.79	0.14	0.77	0.31
TRK602[2]	Tarkus Knob	43°05'	170°58	925	20/27	1526-1978	0.58	0.17	0.24	0.20
UMR189[1]	Urewera	38°41'	177°12	854	12/39	1346-1976	0.66	0.17	2.17	0.32

Source: 1. LaMarche *et al.* 1979a.
2. Norton, 1983a.

1.4 Objectives of this research

This project aims to illustrate the potential usefulness of *Libocedrus bidwillii* for dendroclimatic research. The objectives were as follows:

(1) To develop further chronologies from *Libocedrus bidwillii.* The objective is to extend those current chronologies and double the overall number of sites.

(2) To record the seasonal variation of environmental parameters and the reaction by the tree in terms of its radial growth. The intention is to find out which environmental factors influence tree growth during what time of the year and how strongly.

(3) To investigate any periodicities in the tree-ring data and ascribe biological or other causes. To provide biological data to assist with setting up and interpreting response function analyses.

(4) To use instrumental climate records (data from different weather stations) to model the tree's response to climate.

(5) To use the validated / verified climate response model to reconstruct climate in New Zealand in the period prior to instrumental records.

(6) To discuss the sample methods, filter techniques and any other statistical methods used in the dendroclimatic study.

(7) To demonstrate some new approaches and, through them, to add data about this species to dendroclimatic studies.

1.5 Outline of this thesis

This thesis is divided into seven chapters followed by a series of related appendices.

Chapter 1, the present chapter, briefly introduces the role of dendroclimatology in proxy climatic research. The development of dendrochronology and dendroclimatology is reviewed with emphasis on Australia and New Zealand. The different aspects of research on *Libocedrus bidwillii* is also discussed which sets the background to this thesis. Following this, the overall objectives of this thesis are summarised. Finally, a brief outline of the structure of this work is presented.

Chapter 2 deals with seedling growth under different controlled temperature and moisture conditions. The seasonal growth pattern and the relationship between growth and environmental factors are discussed. The objective of chapter 2 is to provide biological data to assist with setting up and interpreting response function analyses.

Chapter 3 discusses the dendrochronological procedures used for both sampling and analysing the tree-ring materials. It begins with site descriptions, sampling, crossdating and quality of measurement. The different standardisation filters are explored and the autocorrelation in the chronology series are removed. This chapter ends with a discussion of the 'subsample signal strength' or in other words how strong the common ring-width signal is carried back in time as fewer samples are retained.

Chapter 4 explores the relationships between the individual chronologies. Chronologies are compared statistically by cross-correlation analysis with regard to separation distance, differences in altitude and then by looking more closely at the geographical details of inter-chronology correlation.

Chapter 5 is concerned with identifying the climate signals contained in the chronologies. The results are produced by using traditional response function and bootstrap response functions. A multitude of climate variables and time spans are also employed. After this, response function analyses are carried out and significant response functions summarised into four groups based on principal component analysis (PCA) results.

Chapter 6 extends on from the previous chapter with the reconstruction of climate using the multiple regression technique of transfer function analysis. New Zealand summer temperature series and rainfall back to AD 1720 (based on 11 chronologies) and AD 1458 (based on the three longest chronologies) are reconstructed using a verified transfer function and the results discussed.

Chapter 7 summarises the results of the previous chapters, draws conclusions, and ends with a discussion of the implications for future work.

Appendices. There are four parts to the appendices. The first demonstrates the output of electric dendrobands installed on two adult trees in natural environment. The seasonal fluctuation and daily variation of tree growth and environmental factors are analysed. The second comprises chronology summary data for all the sites. The third and fourth contain recorded and reconstructed climate data respectively.

CHAPTER TWO

EFFECTS OF TEMPERATURE AND MOISTURE STRESS ON SEEDLING GROWTH

2.1 Introduction

Libocedrus bidwillii is one of the native conifer species in New Zealand's evergreen conifer-broadleaved hardwood forests. Some former workers (Veblen & Stewart, 1981, 1982; Stewart & Rose, 1989) have studied its ecology. Eleven tree ring chronologies have been established by LaMarche *et al.* (1979a) and Norton (1983a). The oldest chronology in New Zealand produced using this species extends back to AD 1256 (LaMarche *et al.*, 1979a). But, so far, no climate reconstruction has been attempted using the species. In order to use *Libocedrus bidwillii* to reconstruct past climate, it is necessary to determine if it is "sensitive" to climate not only from a statistical viewpoint, but also from a physiological viewpoint. It is important to know how seasonal climate variation affects seasonal growth in *Libocedrus bidwillii*. There have been a lot of physiological studies of other species. For example, Cornelissen (1993) analysed the seasonal and year to year variation of *Gordonia acuminata* seedlings in different light environments. Conner & Day (1988), Hughes *et al.* (1984), Campbell (1985), Rao (1988), Rao & Singh (1985) and Poole (1986) have described a series of experiments on seedling growth of a series of different tree species under water stress and different temperatures. However, no such work has been done on *Libocedrus bidwillii*.

2.2 Methods

2.2.1 Treatment of the seedlings

A randomised complete block design was used in this experiment. On February 4, 1993, 50 two year old *Libocedrus bidwillii* seedlings (Group A) were bought from a Central North Island National Park nursery. In order to increase the accuracy of the experiment, another 50 two year old seedlings (Group B) were bought from the same park on September 2, 1993. Each seedling was planted in a two litre black plastic pot (with drainage holes in the bottom) filled with a crumbled, homogenised, potting mix medium. Two seedlings were harvested for an initial investigation as described below. All the other seedlings were measured (plant height, stem diameter, leaf area and branch length). The data were analysed using cluster analysis (SAS Institute Inc., 1992). Forty-eight seedlings were selected and classified into 12 blocks with 4 morphologically similar seedlings in each block. Four treatments were imposed randomly within each block. The four treatments consisted of two varying temperature regimes: a constant temperature glasshouse, a variable temperature glasshouse; and two soil moisture regimes: fully irrigated and 50% fully irrigated. CD is constant temperature and low moisture, CW is constant temperature and high moisture, HD is variable temperature and low moisture and HW is variable temperature and high moisture. Throughout the experimental period the pots were weighed every two or three days to determine soil moisture losses. Weeds were removed frequently and the soil surface was loosened if crusts formed. Nutrients were supplied at a rate of 5g/pot using a controlled release fertiliser (Osmocote-plus N 16%, P 3.5%, K 10%, S 1.2% plus all essential trace elements, Fe, Cu, B, Mn, Mo, Zn, with 12-14 months longevity at 21°C average soil temperature) on September 3, 1993 for group A and no extra nutrients were supplied to Group B (due to the relative short growth period in the pots of Group B). There were no signs of nutrient stress throughout the experiment. Group B plants were arranged in the same experimental design, and the same methods used as for Group A.

2.2.2 Non-destructive measurements

All seedlings were measured every two weeks (before July 1993 for Group A) or monthly (from July 1993 for both groups) in order to determine plant length, stem diameter at 5 cm height, number of branches, leaf area and total branch length. Only branches > 4mm long were counted and measured. Branches were numbered successively, with the first being the oldest branch nearest to the bottom. Every five branches were labelled using different coloured wires. Leaf area was measured with a portable leaf area measuring machine. It measured the branch stem surface and leaf area together, but, as the stem and leaf area are all green and photosynthetic, the measurements were used directly.

2.2.3 Harvests

Before setting up the experiment, two seedlings were harvested. On July 26, 1993 and January 30, 1994, 3 plants of each treatment were harvested from Group A. Group B was harvested on February 23, 1994 (6 plants for each treatment). The final harvest, when all remaining seedlings were cut was on August 30-31, 1994. The following primary data were collected: plant height (from soil surface to apical meristem), stem diameter, length of branch, leaf area, leaf water potential using a thermocouple psychrometer, length of root, dry weight of roots, dry weight of leaves, dry weight of stem, and soil moisture. Root systems were carefully washed free from soil using a spray gun. The soil was checked thoroughly for living roots that had broken off. Root length was measured by the line intersect method of Tennant (1975). Dry weights were determined after 48 hours in an oven at 70°C. Soil moisture were measured before and after 48 hours in an oven at 105°C.

2.3 Results

2.3.1 Weather and microclimate

Maximum and minimum temperatures in the glasshouses were recorded daily (weekdays) by the staff of the Nursery and Glasshouse Complex, Lincoln University. The day length was calculated from "New Zealand Nautical Almanac 1992-93" (Whitley, 1992) and "New Zealand Nautical Almanac 1993-94" (Lamont, 1993). Total solar radiation came from the "Monthly Climate Report" (Climate Research Unit, 1993, 1994). Figure 2.1 shows that the average day length was shortest in June and increased gradually from winter to summer and decreased gradually from summer to winter. Solar radiation changed more sharply. The lowest value also occurred in June and the highest was in January. The variable temperature treatment was more variable daily and seasonally. The monthly average maximum temperature was up to 34°C in the summer and down to 20°C in the winter. The minimum temperature was always around 10°C. The constant temperature treatment did not vary much all year and the minimum temperature was always higher than the variable temperature treatment minimum. The amount of water applied to the wet treatments was about twice that of the dry treatments throughout the year and a half (Figure 2.1).

2.3.2 Plant size

There were no obvious differences in heights, diameters and branch length until 270 days in Group A, but only 60 days in Group B (Figure 2.3 & 2.5). At the final harvest time (t = 572 days for group A and t = 360 days for group B), HW saplings were the tallest at 55.30cm (group A) and 31.37cm (group B). The two wet treatments (CW and HW) had greater plant heights, diameters and total branch lengths than did the trees in the dry treatments (CD and HD) (Figure 2.2 & 2.4).

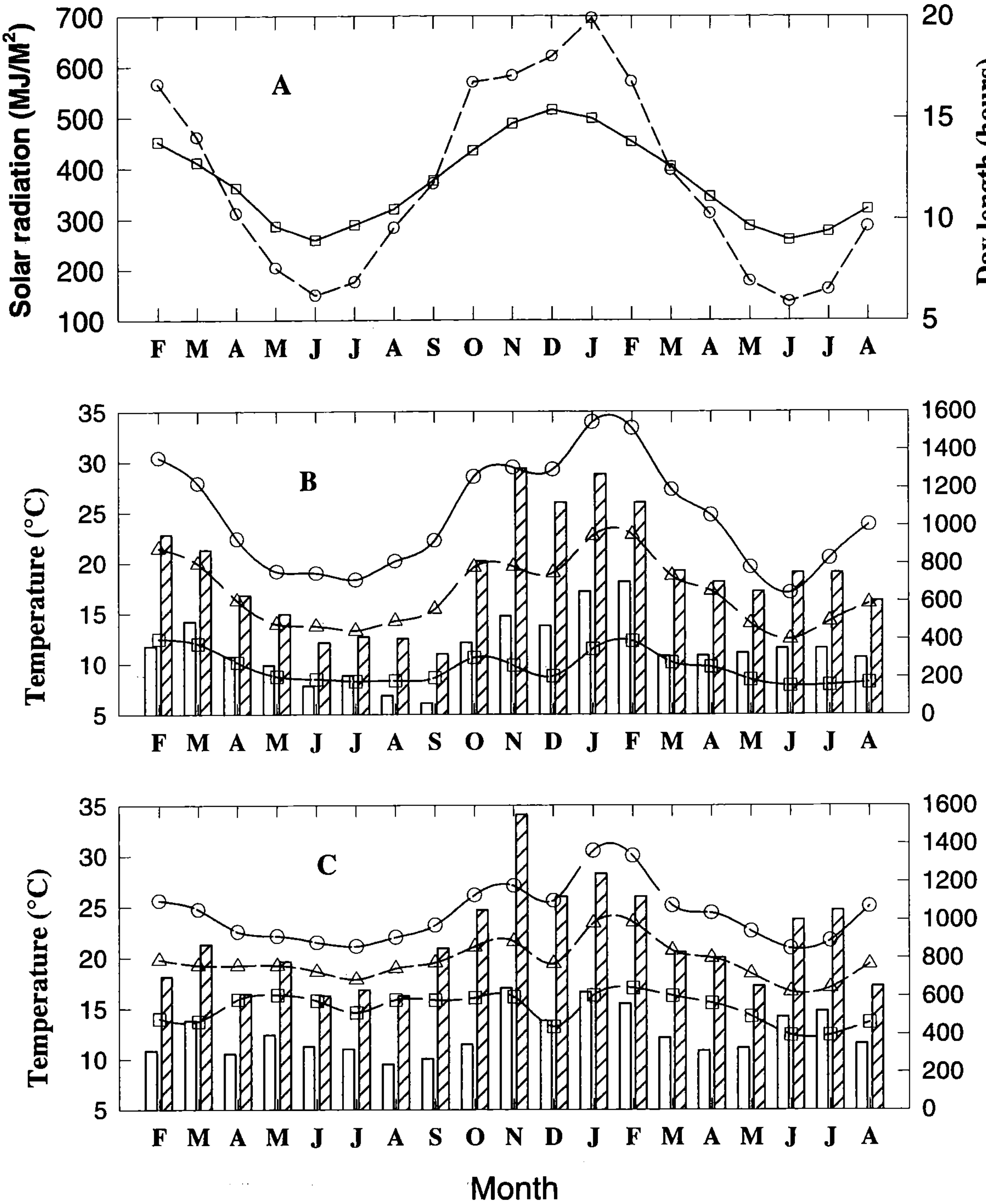


Figure 2.1 Climate data for the experimental period (Feb. 1993-Aug. 1994). A. Total solar radiation (MJ/m^2) and average day length (hours). —⊖— Solar radiation. —⊟— Day length B. Variable temperature treatment. C. Constant temperature treatment. In B and C, the curved lines are mean daily maximum, minimum and average air temperature (°C); the bars are water applied in each treatment (ml/month). ☐ Dry ▨ Wet treatment; —⊖— Maximum —⊟— Minimum —△— Average temperature.

Figure 2.2 The Group A seedlings after 572 days under different treatments. **A.** above ground.

Figure 2.2 The Group A seedlings after 572 days under different treatments. **B.** the roots.

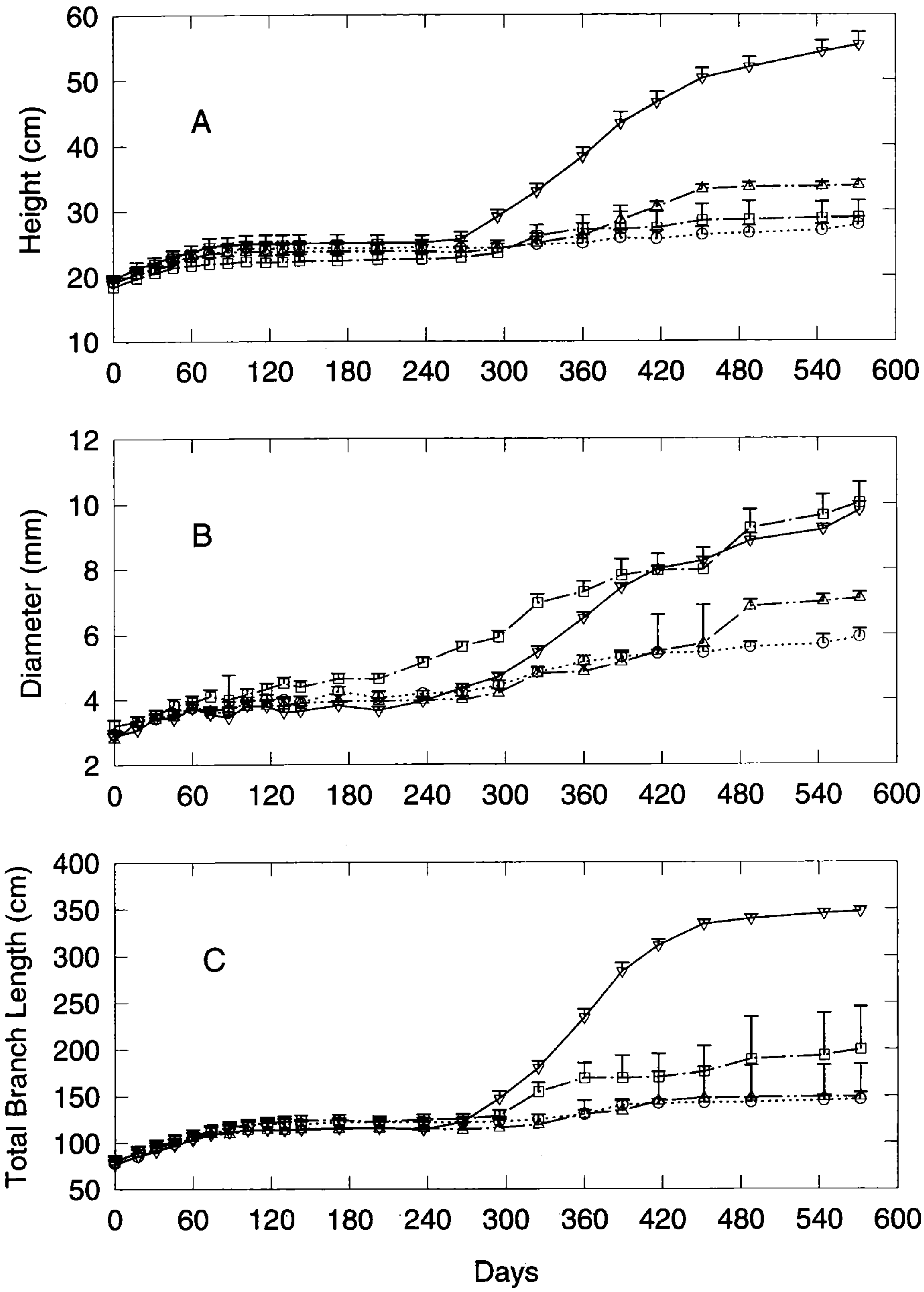


Figure 2.3 Cumulative height, stem diameter and total branch length growth of Group A seedlings under different treatments. Experiment started on February 4, 1993, and day 572 was August 30, 1994. Standard errors shown are one-sided. ····○··· CD, —□— CW, —△— HD, —▽— HW. CD = Constant temperature & Dry moisture; CW = Constant temperature & Wet moisture; HD = Variable temperature & Dry moisture; HW = Variable temperature & Wet moisture.

Figure 2.4 The Group B seedlings after 360 days under different treatments. **A.** above ground.

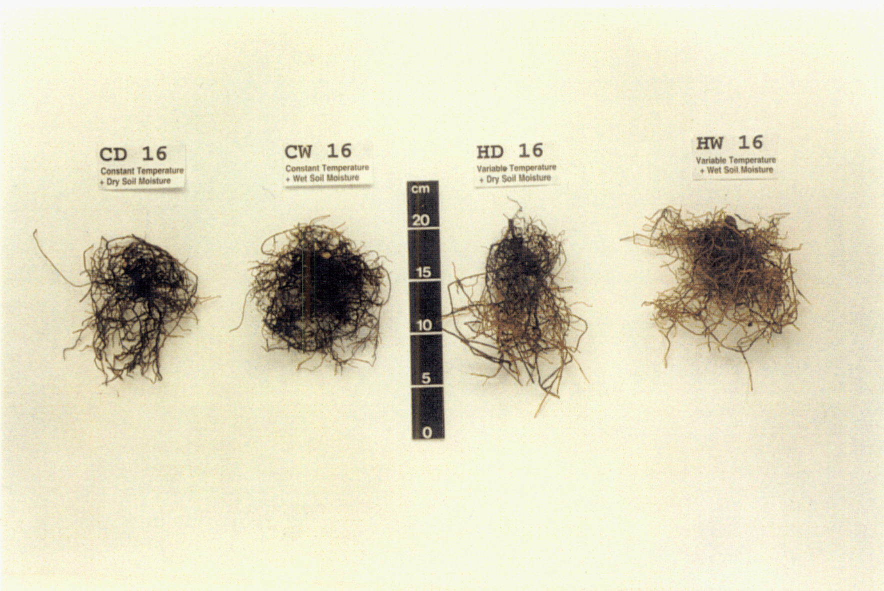


Figure 2.4 The Group B seedlings after 360 days under different treatments. **B.** the roots.

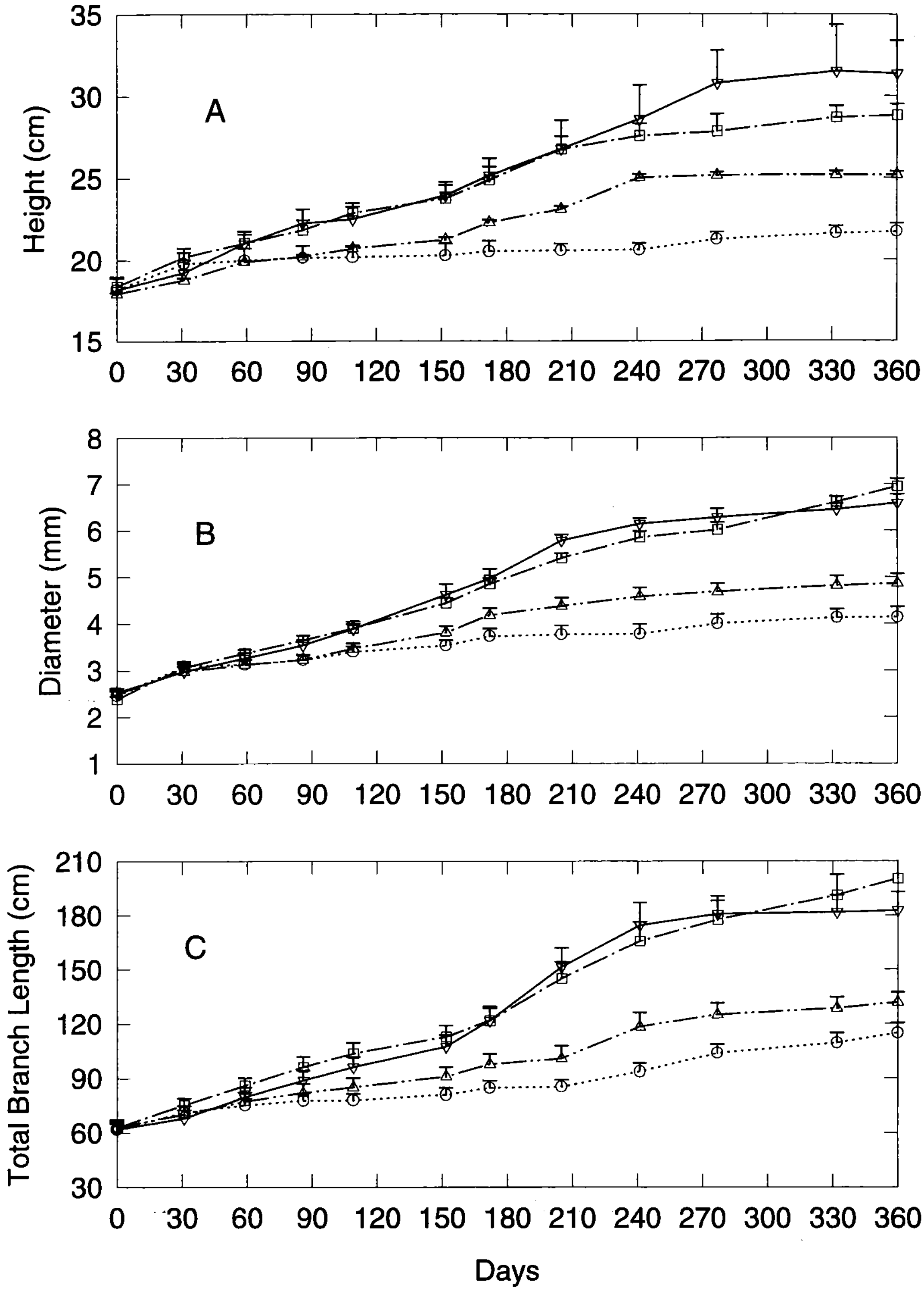


Figure 2.5 Cumulative height, stem diameter and total branch length growth of Group B seedlings under different treatments. The experiment started on September 4, 1993, and day 360 was August 30, 1994. Standard errors shown are one-sided. ···○··· CD, —□— CW, —△— HD, —▽— HW. Refer to Figure 2.3 for explanations of CD, CW, HD & HW.

2.3.3 Whole plant morphology

Table 2.1 Whole plant morphology at t = 0, t = 572 days (group A) and t = 360 days (group B) in four treatments.

	leaf area ratio (cm/g)		root weight ratio		leaf area/stem height ratio (cm^2/cm)	
t = 0	22.42±1.60		0.34±0.0187		1.97±0.04	
t = 572 days (Group A)						
CD	30.43±4.68	ab	0.32±0.0218	a	12.04±3.27	b
CW	32.16±1.00	a	0.30±0.0344	ab	27.65±8.89	a
HD	26.51±1.44	b	0.32±0.0087	a	12.29±2.67	b
HW	28.49±0.67	ab	0.26±0.0354	b	16.44±2.45	b
ANOVA	p<0.05		p<0.05		p<0.05	
t = 360 days (Group B)						
CD	37.34±6.18	b	0.29±0.0582	b	11.96±3.83	b
CW	44.35±2.49	a	0.20±0.0358	c	23.35±5.51	a
HD	28.43±3.95	c	0.35±0.0374	a	9.22±2.26	b
HW	31.66±2.58	c	0.27±0.0164	b	13.67±3.60	b
ANOVA	p<0.0001		p<0.001		p<0.001	

Length of branches at different positions was affected by the different treatments (Figure 2.6). Within all treatments, individual branches at lower positions on the plant were longer. The wet treatment plants (CW & HW) had more branches than the dry treatment plants (CD & HD) in both groups. The branches of well irrigated seedlings (CW & HW) were always longer than those of water stressed seedlings treatments (CD & HD) at all positions (Figure 2.6).

Treatments effects on leaf area ratios (LAR, leaf area per unit of plant dry weight) were in the sequences of CW > CD > HW > HD in both groups. However, root weight

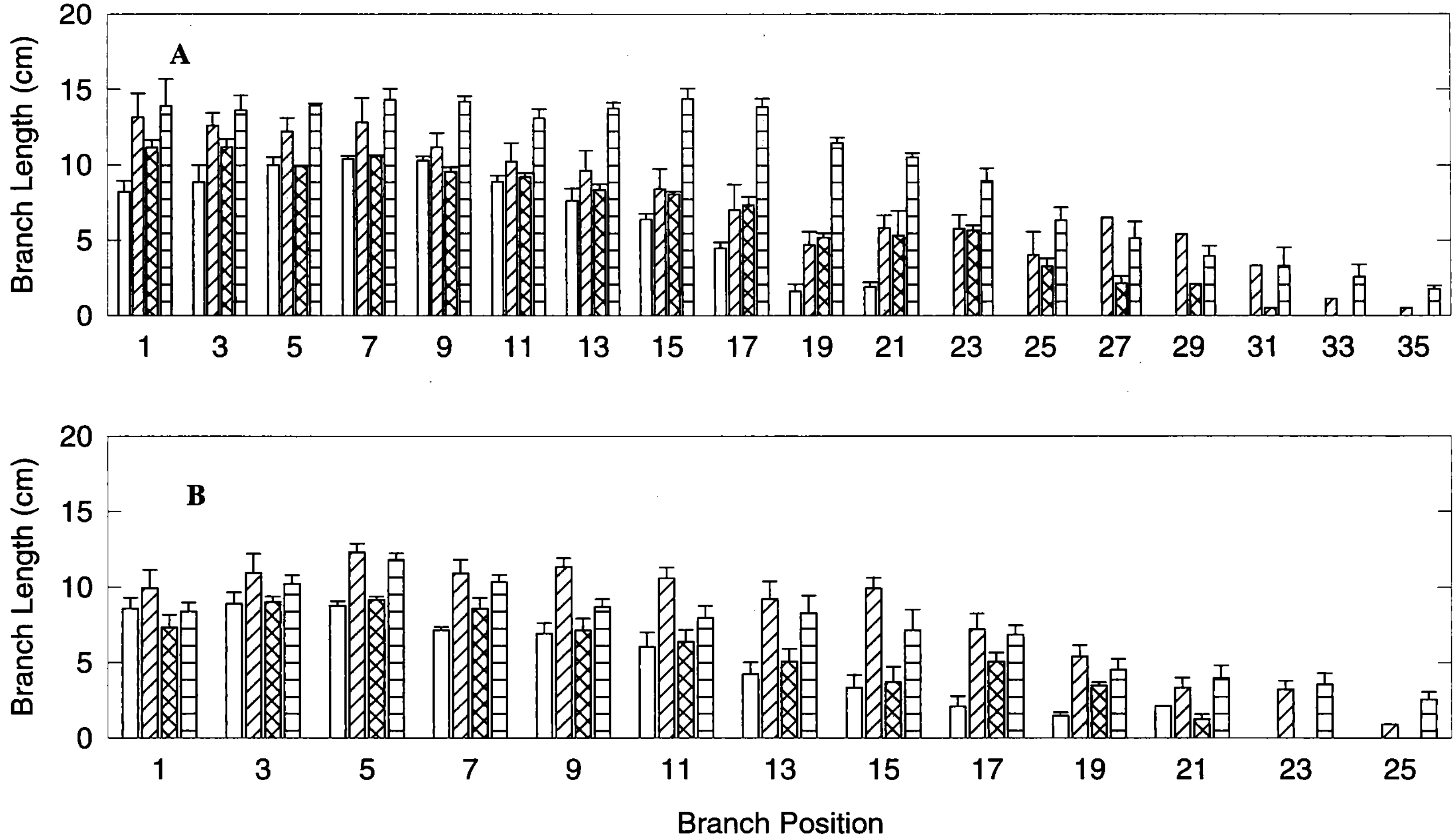


Figure 2.6 The average length of branches at a given position on the third year seedlings. A. Group A at t = 572 days. B. Group B at t = 360 days. Data are given separately for seedlings grown at different treatments. Standard errors are one-sided. In both A and B: CD, CW, HD, HW. Refer to Figure 2.3 for explanations of CD, CW, HD & HW.

Table 2.2 Performance of *Libocedrus bidwillii* seedlings under four contrasting treatments (sd = standard deviation. Means with the same letter are not significantly different in Duncan's multiple range test. Results of ANOVA are given as: * = p<0.05; ** = p<0.01; *** = p<0.001).

	Group A									Group B					
	August 1993			January 1994			August 1994			February 1994			August 1994		
	mean		sd	mean		sd	mean		sd	mean		sd	mean		sd
Plant dry weight (g)															
CD	6.86	a	0.77	7.37	b	0.70	10.75	c	0.75	4.53	b	0.72	6.76	b	0.85
CW	6.68	a	1.40	12.90	a	2.82	25.36	ab	12.21	7.03	a	1.24	15.14	a	3.40
HD	6.49	a	1.74	7.93	b	1.40	15.40	bc	2.29	5.80	a	1.22	8.08	b	1.45
HW	7.16	a	2.13	12.00	a	0.50	31.97	a	5.72	6.67	a	1.78	12.97	a	1.94
ANOVA	*			**			*			**			***		
Plant height (cm)															
CD	25.40	a	2.15	25.50	a	3.34	27.78	b	3.21	21.13	a	2.79	21.72	c	1.96
CW	23.27	a	3.97	29.53	a	3.18	28.53	b	7.74	24.72	a	3.18	28.82	ab	2.55
HD	24.13	a	4.65	26.93	a	1.40	33.53	b	2.06	22.42	a	3.10	25.17	bc	3.62
HW	25.47	a	3.85	32.30	a	5.34	55.30	a	5.57	24.95	a	2.40	31.37	a	7.58
ANOVA	*			*			***			*			**		
Stem diameter (mm)															
CD	4.53	a	0.42	5.02	b	0.73	5.92	b	0.69	3.86	a	0.50	4.12	c	0.85
CW	4.50	a	0.65	6.68	a	0.62	10.03	a	1.86	4.78	a	0.49	6.95	a	0.64
HD	4.18	a	0.60	5.45	b	0.35	7.10	b	0.58	4.42	a	0.50	4.86	b	0.78
HW	4.58	a	0.62	6.68	a	0.81	9.78	a	0.78	4.84	a	1.02	6.59	a	0.71
ANOVA	*			**			**			*			***		

Branch length (cm)															
CD	117.33	a	11.18	120.67	a	14.46	142.85	b	22.14	89.50	b	15.34	106.34	b	26.21
CW	123.63	a	16.45	192.90	a	30.69	225.53	b	86.68	115.82	a	22.35	195.10	a	48.83
HD	128.40	a	17.94	142.37	a	19.62	198.93	b	23.20	104.67	ab	16.62	119.13	b	30.24
HW	132.87	a	33.54	189.27	a	41.35	347.05	a	14.24	116.00	a	28.58	173.62	a	48.14
ANOVA	*			*			**			*			***		
Leaf area (cm^2)															
CD	230.57	a	45.10	244.05	a	62.10	326.91	b	55.42	156.68	b	32.61	255.84	c	68.20
CW	222.97	a	35.03	381.42	a	64.32	810.65	a	373.99	257.79	a	62.37	675.95	a	178.93
HD	209.12	a	52.89	270.82	a	142.68	410.44	b	83.70	207.11	ab	48.36	229.76	c	55.56
HW	253.16	a	99.83	452.65	a	57.25	908.62	a	149.66	238.03	a	65.97	409.83	b	64.86
ANOVA	*			*			*			**			***		
Above ground biomass / under ground biomass ratio															
CD	2.43	a	0.08	1.80	b	0.32	2.10	b	0.21	2.00	a	0.38	2.62	b	0.69
CW	2.43	a	0.34	2.87	a	0.06	2.34	ab	0.36	2.13	a	0.41	4.20	a	1.19
HD	2.51	a	0.35	2.09	b	0.32	2.09	b	0.08	1.76	a	0.25	1.90	b	0.36
HW	2.89	a	0.70	2.97	a	0.18	2.87	a	0.48	1.94	a	0.44	2.66	b	0.22
ANOVA	*			**			*			*			**		
Root length / root biomass ratio (m/g)															
CD	10.59	ab	1.30	9.98	a	0.32	8.45	a	1.95	8.72	a	2.18	6.83	a	1.04
CW	11.12	a	0.33	7.70	a	0.76	7.21	a	3.19	7.46	a	1.76	6.01	ab	1.14
HD	9.06	bc	0.65	9.46	a	1.91	6.60	a	1.01	8.65	a	2.47	5.32	b	1.26
HW	8.30	c	0.26	8.19	a	0.26	6.48	a	0.82	8.08	a	2.03	5.30	b	0.22
ANOVA	*			*			*			*			*		

ratios (RWR, root dry weight relative to plant dry weight) were larger in both dry treatments (CD and HD) than in wet treatments. Leaf area relative to stem height (LSR) was larger in CW seedlings than in seedlings from the other three treatments. Differences between highest and lowest LAR, RWR and LSR, respectively, were 21%, 24% and 130% in group A and 60%, 75% and 153% in group B.

2.3.4 Seasonal variation in growth

In group A, all the treatments had similar growth rates in the first autumn and growth nearly stopped during the first winter (Figure 2.7). The growth rates in the following spring, summer and autumn were strongly influenced by the different treatments. HW had the highest growth rate, CD had the lowest growth rate for all three parameters (plant height, stem diameter and branch length respectively). Plant height and branch length nearly stopped growing during the second winter but stem diameter kept increasing. The highest growth rates in all three parameters were achieved in HW in summer (0.15cm/day in plant height, 0.028mm/day in diameter and 1.45cm/day in total branch length). The diameter growth rate was the greatest in CW in spring and winter (0.012mm/day in spring and average 0.011mm/day in winter). Plant height and branch length growth rate were virtually nil in all treatments during winter.

In Group B, the growth rates of the two wet treatments (CW and HW) were higher throughout the year (Figure 2.8). CD had the lowest growth rate in all four seasons. The plants in all four treatments grew throughout the year, but the growth rate in winter was much slower than that during the other three seasons.

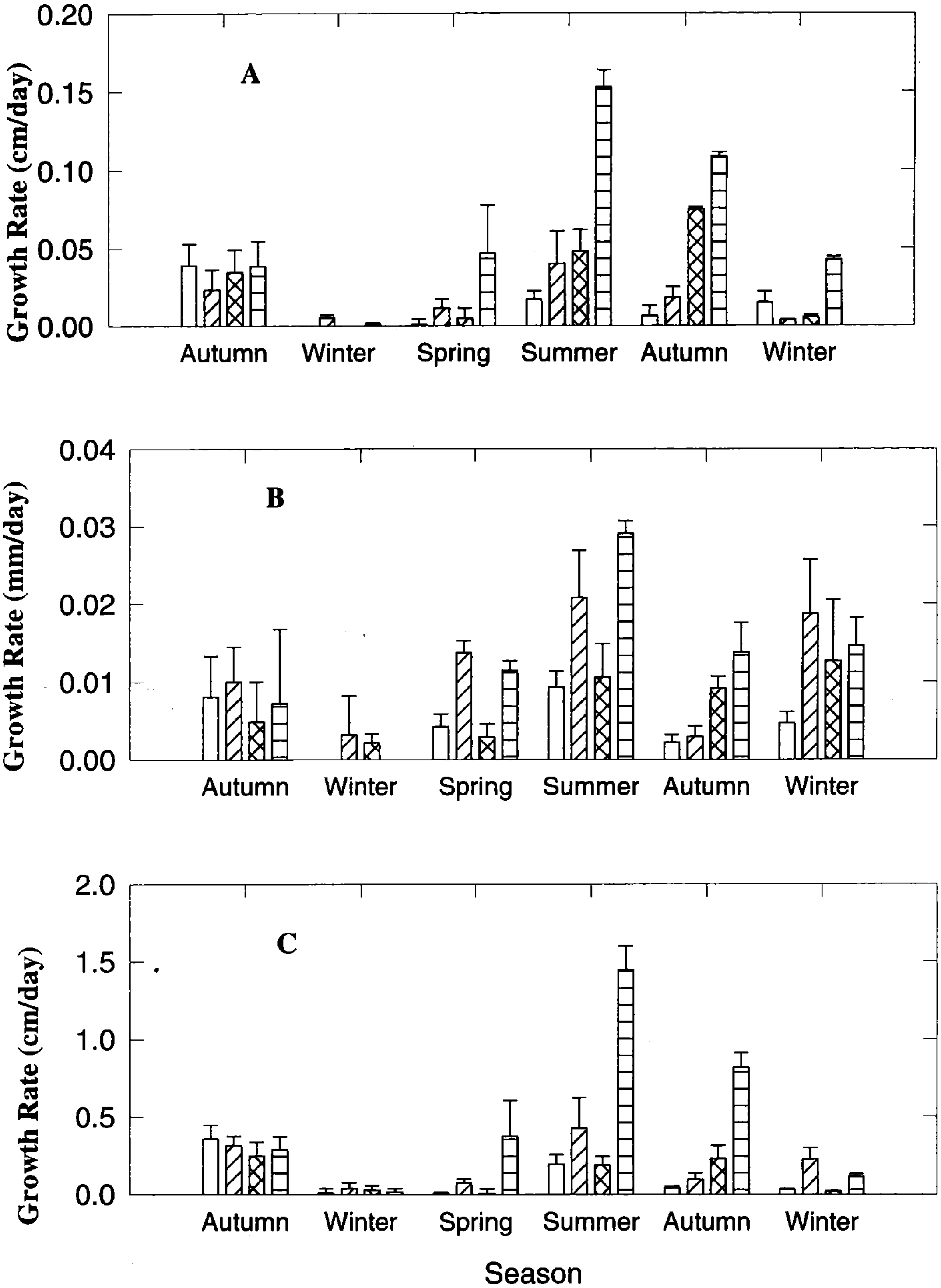


Figure 2.7 Growth rates for plant height, stem diameter and branch length in four seasons of different treatments in Group A. Standard errors given are one-sided. A. Plant height. B. Stem diameter. C. Total branch length The bars are: CD, CW, HD, HW. Refer to Figure 2.3 for explanations of CD, CW, HD & HW.

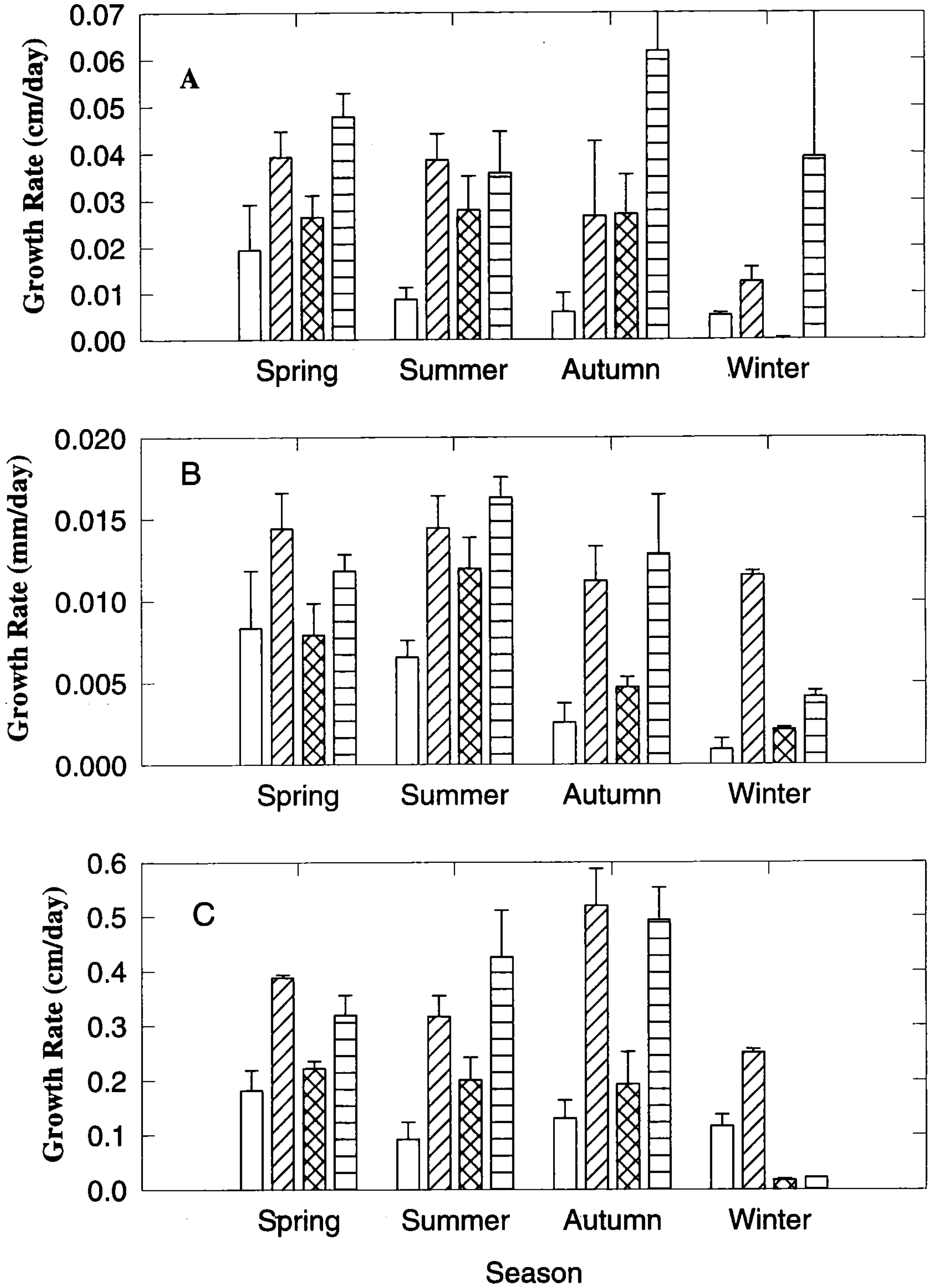


Figure 2.8 Growth rates for plant height, stem diameter and total branch length in four seasons of four different treatments in Group B. Standard error are given one-sided. A. Plant height. B. Stem diameter. C. Total branch length. The bars are: ▭ CD, ▨ CW, ▩ HD, ▤ HW
Refer to Figure 2.3 for explanations of CD, CW, HD and HW.

2.3.5 The interaction of growth and climate factors

There were some significant correlations between environment factors and growth rates of plant height, stem diameter and branch length.

Table 2.3 The correlation between plant growth rate and climate factors.

	Max. Temp.	Min. Temp.	Ave. Temp.	Radiation	Day length
Plant height					
CD	.0921	-.3202	-.0487	.2557	.2245
CW	.4717*	-.1928	.3056	.7444***	.7631***
HD	.6525**	.8032***	.7093***	.5578*	.5234*
HW	.8189***	.6082**	.7971***	.6113**	.6854**
Stem diameter					
CD	.2080	-.2303	.0789	.3138	.3243
CW	.4036	-.2268	.2382	.3700	.4266
HD	.4702*	.4607	.4836*	.4484	.4376
HW	.7118***	.4719*	.6798*	.6108**	.6286**
Branch length					
CD	.0869	-.2991	-.0450	.3016	.2829
CW	.2821	-.4171	.0678	.4311	.5440*
HD	.5936**	.6970**	.6376*	.5884*	.5775*
HW	.8671***	.6772**	.8520***	.7886***	.7994***

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 2.3 shows that there was no statistically significant correlation between the growth rates of all three parameters for trees receiving the CD treatment with any climate factors. There were higher correlations between growth rate and environmental factors in the variable temperature treatment trees (HD and HW) compared with the constant temperature treatment trees (CD and CW). The growth rates in constant temperature treatment trees (CD and CW) had a negative correlation with minimum temperature and a positive correlation with maximum temperature. Water was only significantly correlated with variable temperature treatments (HD and HW). Solar radiation (monthly total, MJ/M^2) and day length (monthly average, hours) were significantly correlated with all three growth parameters in HW trees, but were only significantly correlated with plant height growth rate in CW, HD and branch length growth rate in HD trees.

2.4 Discussion

At the end of the experiment, trees from wet treatments were larger than those from dry treatments. Water is a limiting factor controlling growth of trees under water-stress conditions. For the same moisture treatments, variable temperature treatment trees grew more than constant temperature treatment trees. This was because the variable temperature treatments normally had higher day time temperatures and lower night temperatures. The plants therefore had higher photosynthetic rates during the day and lower respiration rates at night.

There was large seasonal variation in stem elongation, stem diameter and branch length growth of seedlings of *Libocedrus bidwillii.* The patterns of this variation were clearly related to different temperature and soil moisture treatments. Growth started for almost all treatments at the end of September and was completed by the end of April. By the end of October, the fully watered trees had began a period of rapid growth while the stressed trees were still quiescent.

While the temperature in the constant temperature treatment did not fluctuate markedly throughout the year, there was still seasonal growth variation. This was due to the seasonal variation of solar radiation and day length. These two factors had a similar pattern but solar radiation variation was sharper than day length.

The growth rates of the different parts of the seedlings were different. In group A, HW trees grew the fastest in height and branch length, but CW trees grew the fastest in diameter. Constant temperature treatments had larger leaf area ratio (LAR) than variable temperature treatments. The possible reason is that higher temperature at night under the constant temperature treatment lead to higher respiration, with a consequent need for higher photosynthesis, hence plants must grow more leaves (leaf area) to live under this environment. Because of water stress, plants from the two dry treatments had higher root weight ratios. More roots can lead to more effective water use as has been shown in many other studies (Conner & Day, 1988; Hughes *et al.*, 1984).

2.5 Chapter conclusions

1. The seedlings of *Libocedrus bidwillii* are sensitive to climate factors. Temperature, soil moisture, day length and solar radiation significantly influenced seedling growth. Greatest growth was at high soil moisture and under a variable temperature regime (HW).

2. There was obvious seasonal variation in the growth of seedlings. Growth starts in spring, is highest in summer and nearly stops in winter.

3. Constant temperature treatment trees (CD & CW) had a higher leaf area ratio and dry soil moisture treatment trees (CD & HD) had higher root weight ratios.

4. More branches developed on high moisture treatment trees (CW & HW) and also every branch from these trees was longer than those on dry treatment trees.

CHAPTER THREE
DENDROCHRONOLOGICAL ANALYSIS

3.1 Introduction

This chapter discusses the development of chronologies from 23 sites. They consist of 12 new sites, 5 updated and 4 non-updated sites sampled by LaMarche *et al.* (1979a) and 2 non-updated sites sampled by Norton (1983a).

Site selection is the first step in a dendrochronological study. The first section of this chapter discusses this aspect. Cross-dating is widely recognised as the most important concept in dendrochronology. The quality of chronology and subsequent climate reconstructions are strongly dependent on the strength of the cross-dating. The second section discusses cross-dating, ring-width measurements and the quality of these measurements. Program COFECHA was used to check the quality of the cross-dating (Holmes *et al.*, 1986; Grissino-Mayer *et al.*, 1992). The general statistics of COFECHA have been given for each site in the third section.

After having obtained satisfactory confirmation of the measurements, the next step was standardisation. The fourth and fifth sections of this chapter discuss and compare different alternative standardisation approaches. The fourth section is focused on different detrending methods and the climate consideration of standardisation. The fifth section discusses autocorrelation removal. Finally, a sub-sample signal strength (SSS) (Briffa, 1984) was chosen to delimit the useable chronology period for climate modelling used in later chapters (i. e. Chapter 5 and Chapter 6).

3.2 Site description and sampling

The most appropriate regions for dendroclimatic investigations tend to be those where trees grow at or near their climatic distributional limit and where climatic factors still strongly affect tree-ring variability without being so strong that virtually no growth occurs. Another favoured approach, has been the selection of the oldest possible trees. In this study, site selection concentrated, as far as possible, on mature forests in which no previous logging or other type of disturbance was known to have occurred. A few of the stands also contained some dead trees (such as sites HIT, TKP, TOC; refer to Appendix 2 for details of site descriptions). Some other sites largely included younger trees (such as sites FLG, WBF). The updated sites were the same places where the original authors sampled. The criteria of site selection for the new sites were that:

(1) there were no obvious signs of recent disturbance;
(2) some old (large) trees (with DBH > 50 cm) were present;
(3) the site was considered to be climatically limiting.

Using the above criteria, sites in the North Island were selected along similar latitudes but across the breadth of longitudes so as to encounter the very different rainfall pattern from the east to west coast. The South Island, sites were selected from the north to the south, reflecting different temperature regions. At Mt. Hauhungatahi, three separate sites were sampled at different altitudes to check the altitudinal response (Figures 3.2-4).

The location of the sampling sites are shown in Figure 3.1 and the corresponding site characteristics are summarised in Table 3.1.

A subjective decision was made in the choice of individual trees for coring in each stand (Palmer, 1989). Deformed or damaged trees, or those growing close to large neighbours were avoided. Because the old and large trees often had narrow rings

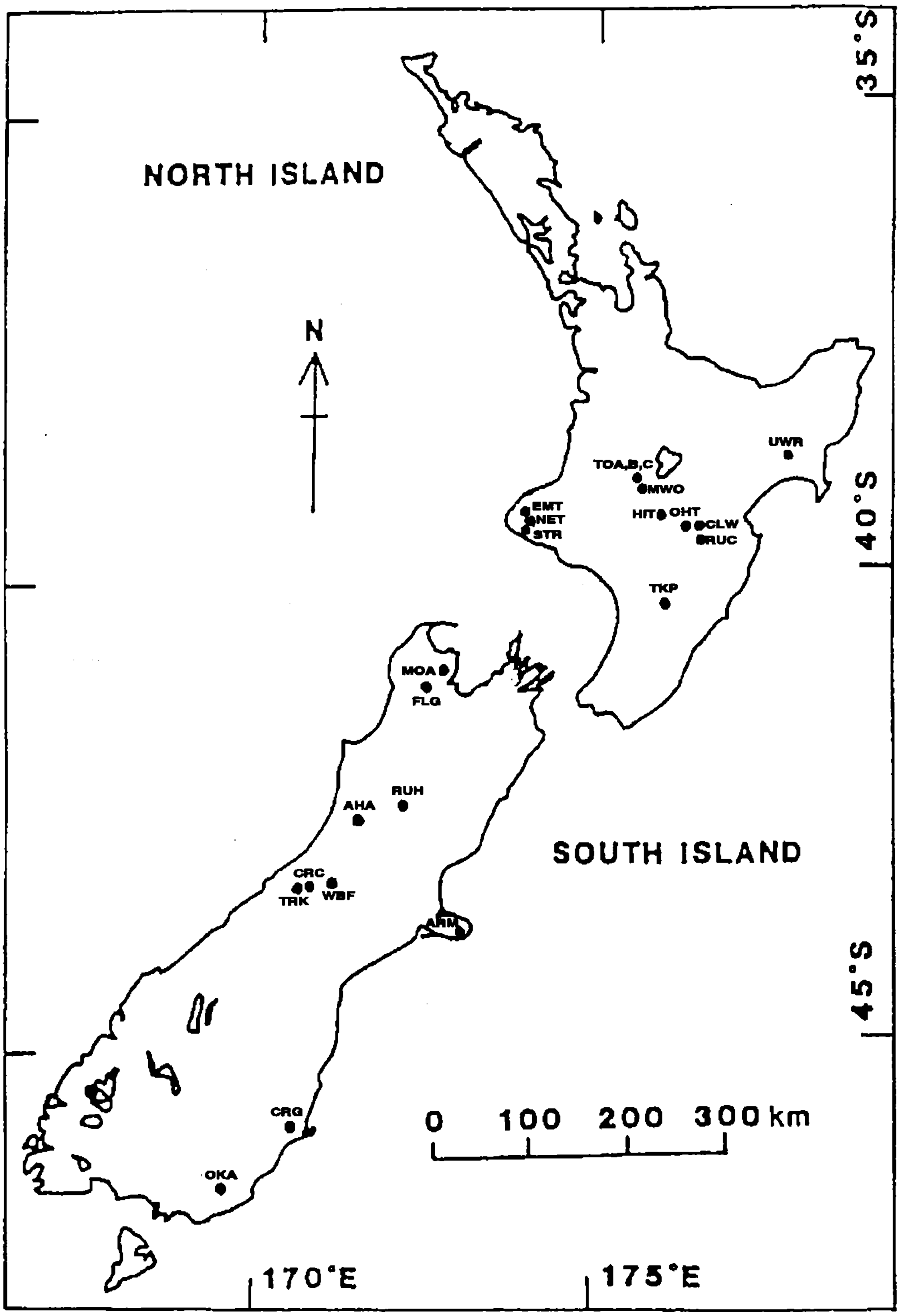


Figure 3.1 The location of the *Libocedrus bidwillii* chronology sites. Site names are given in Table 3.1 and for specific site details refer to Appendix 2.

Table 3.1 Characteristics of 23 *Libocedrus bidwillii* sites

Abbr.	Site name	Latitude	Longitude	Altitude (m)
Non-updated sites				
ARM[1]	Armstrong Reserve	43°50'	173°00'	731
CRC[2]	Cream Creek	43°05'	170°59'	800
CRG[1]	Mount Cargill	45°50'	170°32'	576
MWO[1]	Mangawhero R. B.	39°21'	175°29'	1000
OKA[1]	Owaka	46°23'	169°27'	305
TRK[2]	Tarkus Knob	43°05'	170°58'	925
Updated sites				
AHA[1]	Ahaura	42°23'	171°48'	244
EMT[1]	Mount Egmont	39°15'	174°05'	1050
NET[1]	North Egmont	39°17'	174°06'	991
TKP[1]	Takapari	40°04.3'	175°59'	838
UWR[1]	Urewera	38°40.7'	177°11.8'	854
New sites				
CLW	Clear Water	39°37.5'	176°06.3'	1220
FLG	Batten Range /Flanagans Hut)	41°16.3'	172°35.5'	950
HIT	Hihitahi	39°32'	175°44'	976
MOA	Moa Park	40°56'	172°56'	1036
OHT	Ohutu Ridge	39°37.3'	176°07.7'	1140
RUC	Ruahine Corner	39°38.2'	176°10.7'	1200
RUH	Rahu Saddle	42°18.95'	172°07'	672
STR	Stratford Side (East Egmont)	39°18.5'	174°07.25'	860
TOA	Hauhungatahi site A, Tongariro	39°14'S	175°26'E	1160
TOB	Hauhungatahi site B, Tongariro	39°14'S	175°26'E	1100
TOC	Hauhungatahi site C, Tongariro	39°14'S	175°26'E	1000
WBF	Werberforce	43°04'S	171°16.5'E	780

Source: 1 LaMarche's site (LaMarche *et al.*, 1979a); 2 Norton's site (Norton, 1983a).

Figure 3.2 *Libocedrus bidwillii* growth rings (approximately the natural size).

Figure 3.3 Mt. Hauhungatahi (Tongariro National Park), showing the altitudinal ranges for woody species from 750m to timberline (1160M). Three sites (TOA, TOB, TOC) were sampled here.

Figure 3.4 Typical pocket of *Libocedrus bidwillii* in an area of beech (*Nothofagus spp.*) forest (Rahu Saddle, South Island; site RUH).

Figure 3.5 Sampling a *Libocedrus bidwillii* tree at Ruahine Corner, North Island (site RUC).

towards their bark and this often presented cross-dating difficulties, so some younger trees (with relatively small DBH) were always cored from the available stand.

Samples were obtained using increment borers (Figure 3.5); 20 - 30 trees were cored from each site with 2 or 3 cores taken from each tree and stored in plastic straws. In addition, some cross-sections were taken from some sites which had dead trees present.

3.3 Cross-dating and measurements

3.3.1 Laboratory procedures

Core mounting and sample preparation followed standard procedures (see Stokes & Smiley, 1968). Cores were fixed to a wooden mount using a water-soluble glue. After a few days, the cores were sanded using increasingly fine sand paper to get a smooth, polished surface.

As mentioned in the introduction, cross-dating is the most important principle of dendrochronology. The yearly ring-widths must crossdate among radii within a tree and among different trees in a given stand, as well as among ring-width patterns of neighbouring stands (Fritts, 1976). Cores from each site were examined under a binocular microscope and visual cross-matching (cross-dating) was attempted. The "marker" years (some very narrow or wide years) were used to help with cross-dating. All the cored sites have been cross-dated (average 80% of cores were cross-matched). Some cores were rejected because they had indistinct ring boundaries or weak cross-dating with other cores in the site. Because the growing period of trees in NZ covers two calendar years, the years were designated by the year in which growth commenced (Palmer & Ogden, 1983). Thus when the outermost ring was formed in the 1992-93 summer it was designated as the 1992 ring. Ring-widths were measured to the nearest 0.01mm using a computer-based measuring system and program TRIMS (Madera Software, 1988). All the measuring was done at the Forest Research Institute (FRI), Christchurch.

3.3.2 Quality control of the measurements

In order to check the quality of the tree-ring measurements, at least 3 cores were randomly picked from each site and remeasured. Following this, the verify program in ITRDBLIB (Grissino-Mayer *et al.*, 1992) was used to check the measurements. The verification technique was adapted from Fritts (1976) and is designed to read two files containing ring measurements as produced by the standard measuring program TRIMS, and the measurements of the first file are verified by comparison with measurements from the second file. The first file (the first time measurement) is assumed to be the file to be verified, while the second file is assumed to contain the repeated measurements.

Table 3.2. The comparison of the re-measurements.

Site	Core 1			Core 2			Core 3		
code	I.D.	CORR	MSD	I.D.	CORR	MSD	I.D.	CORR	MSD
AHA	26435-2**	0.976	0.007	26436-1**	0.992	0.003	26440-2**	0.987	0.003
CLW	CLW7-2**	0.972	0.003	CLW8-3**	0.985	0.005	CLW18-2**	0.957	0.006
EMT	DAF1-1*	0.955	0.021	DAF5-1*	0.971	0.010	DAF6-3**	0.964	0.008
FLG	FLG17-2**	0.979	0.002	FLG18-1**	0.974	0.006	FLG23-2**	0.906	0.012
HIT	H21-100**	0.969	0.005	H16-50**	0.971	0.002	MT5-55**	0.977	0.008
MOA	MOA13-3*	0.407	0.043	MOA17-1**	0.972	0.002	MOA20-2**	0.978	0.005
NET	NET6-3**	0.984	0.006	NET8-1**	0.973	0.004	NET11-2*	0.947	0.012
OHT	OHT2-1**	0.980	0.003	OHT7-2**	0.962	0.008	OHT9-2**	0.978	0.003
RUC	RUC14-1**	0.964	0.008	RUC28-2**	0.960	0.007	RUC30-2**	0.980	0.004
RUH	RUH1-2**	0.946	0.004	RUH7-3**	0.960	0.003	RUH11-2**	0.988	0.002
STR	STR3-1*	0.795	0.038	STR4-2**	0.953	0.008	STR5-2*	0.967	0.020
TKP	TAK2-1*	0.782	0.049	TAK14-2**	0.983	0.967	TAK15-1**	0.985	0.002
TOA	26405-3**	0.950	0.003	26416-3**	0.991	0.004	26422-2**	0.946	0.006
TOB	MU15-2**	0.975	0.004	Mu18-3**	0.984	0.003	MU27-1**	0.971	0.004
TOC	AKU19-2**	0.933	0.007	26428-1**	0.932	0.005	26431-2**	0.939	0.002
UWR	KAI1-3**	0.950	0.005	KAI7-2**	0.974	0.005	KAI11-2**	0.947	0.002
WBF	26467-2**	0.964	0.004	26469-1**	0.966	0.008	26480-1**	0.977	0.003

Note: I. D. is the core identification, I.D. with a '*' means confidence level was accepted at 0.05 and '**' means accepted at 0.01 level. CORR is correlation coefficient and MSD is mean square differences. Refer to Table 3.1. about the site code.

In Table 3.2, I.D. is the core which was measured twice. CORR is the correlation coefficient between the two data sets which should be at or near 1.00 for similar data sets. Mean square differences (MSD) is the sum of all squared differences divided by the number of observations. This is the value used in determining whether to reject or accept the measurements.

From table 3.2, there are 86.3% remeasured cores accepted at the 1% level, all other cores are accepted at the 5% level. The measurements are highly acceptable.

3.3.3 Quality of the cross-dating

After checking the quality of the tree-ring measurements, a thorough check was made of the strength of the cross-matching between cores and trees using the computer program COFECHA, developed by Holmes *et al.* (Holmes, 1983; Holmes *et al.*, 1986; Grissino-Mayer *et al.*, 1992).

COFECHA is intended to assist data quality control by thoroughly examining all series from the first to the last value. It thus gives the dendrochronologist an independent tool to confirm the accuracy of dating and measurement. It may be used to assist in deciding to accept or reject series or portions of series for inclusion in a site chronology or for other analyses. Before cross-dating and measurement problems are identified, every series is transformed by the program which includes: (1) A cubic smoothing spline with 50% cutoff of 32 years fitted to the series, and each value of the series is divided by the corresponding value of the spline curve, resulting in a series without trend or long waves and with a mean of unity. (2) The persistence of earlier periods of growth in the smoothed series is removed by autoregressive modelling, which may remain after the spline fit. (3) The transformed measurement series is saved on a direct access file for subsequent testing. The series is added to an accumulating "Master" series and a record is kept of the number of series contributing to the "Master" series. (4) After all series have been transformed, the accumulated "Master" series is divided by the contributing number of series to give an arithmetic mean series of all transformed dated series. The resulting "Master Dating Series" is intended to embody the cross-dating characteristics of the site.

After this, each transformed series is tested against the Master Dating Series. To avoid the possibility of any bias, the Master Dating Series is reproduced without the inclusion of the series under consideration.

A series is tested segment by segment against the adjusted Master Dating Series for cross-dating and general measuring accuracy. Correlations for each 50-year segment of the series under examination are matched with the Master Dating Series at the point of cross-dating. For each segment the correlation is verified to be positive and significant at the 99% level. The correlation is also checked to see that it is higher when matched as dated than at any position shifted up to ten years earlier (-10) or later(+10) from the dating. Experience indicates that ten years on either side is adequate to locate most cross-dating errors, and will also catch errors made by skipping or repeating a decade while measuring (Grissino-Mayer *et al.*, 1992).

Successive segments are stepped 25 years, giving a 50% overlap. In order to test to the ends of the series, the first segment begins with the first year of the series and the last ends with the last year; all segments are of the same length. Intermediate segments begin on years evenly divisible by the lag. The overlap of the first two and the last two segments is therefore usually greater than the lag. For each series a note is made of segments which correlate poorly with the corresponding segments of the Master Dating Series (the mean of all other series) or which correlate higher at a position other than the position as dated. Single values are noted which have the effect of strongly lowering or raising the correlation of each series with the mean of all other series.

Table 3.3 gives the general statistics of the 23 sites. It includes the number of cores and trees, the chronology period, mean correlation with the Master Dating Series, unfiltered data series statistics and filtered data series statistics. The table (Table 3.3) includes 5 sites which used the original measurements made by LaMarche *et al.*

Table 3.3. The descriptive statistics of COFECHA outputs for 23 chronology sites

Site	Total trees / cores (no. in parentheses refer to the contribution by this thesis)	Period	Mean Corr. with Master	Unfiltered					Filtered (Prewhitened)		
				Mean msmt	Max msmt	Std dev	Auto corr	Mean sens	Max value	Std dev	Auto corr
AHA[*,1]	32 (15) / 59 (26)	1525 - 1992	.511	.60	4.35	.312	.818	.228	2.41	.280	-.023
ARM[#,1]	22 / 46	1446 - 1958	.644	.81	2.92	.327	.775	.222	2.34	.281	-.027
CLW	(18 / 45)	1450 - 1991	.516	.69	2.78	.288	.787	.212	2.37	.275	-.021
CRC[#,2]	15 / 25	1460 - 1978	.464	.58	2.99	.282	.792	.263	2.41	.284	-.001
CRG[#,1]	12 / 43	1492 - 1975	.598	.89	2.61	.324	.793	.197	1.01	.258	-.017
EMT[*,1]	22 (8) / 60 (12)	1616 - 1990	.618	.98	3.06	.391	.727	.241	2.31	.300	-.009
FLG	(20 / 33)	1683 - 1991	.560	.79	3.00	.299	.734	.209	2.23	.314	-.013
HIT	(49 / 52)	1431 - 1991	.536	.68	3.80	.297	.770	.255	2.26	.268	-.023
MOA	(20 / 49)	1490 - 1991	.540	.47	2.26	.228	.838	.222	2.30	.267	-.014
MWO[#,1]	19 / 69	1464 - 1976	.527	.50	2.80	.211	.780	.199	2.27	.268	-.023
NET[*,1]	35 (10) / 69 (16)	1625 - 1990	.597	.79	3.63	.353	.806	.232	2.27	.313	-.013
OHT	(17 / 40)	1585 - 1991	.546	.82	3.72	.317	.773	.203	2.21	.281	-.002
OKA[#,1]	14 / 47	1732 - 1976	.566	.99	3.42	.419	.815	.212	1.38	.279	.008
RUC	(29 / 73)	1473 - 1991	.545	.71	2.59	.282	.780	.208	2.32	.269	-.009
RUH	(20 / 40)	1560 - 1992	.514	.52	2.96	.285	.811	.247	2.46	.299	-.021
STR	(7 / 11)	1626 - 1990	.489	.94	3.15	.380	.798	.214	2.19	.306	-.012
TKP[*,1]	37 (11) / 63 (17)	1256 - 1992	.590	.66	3.07	.308	.820	.222	2.34	.284	-.013
TOA	(25 / 43)	1511 - 1992	.545	.60	2.74	.249	.755	.215	2.28	.299	-.024
TOB	(15 / 27)	1332 - 1992	.569	.50	2.65	.249	.820	.235	2.25	.269	-.022
TOC	(14 / 24)	1213 - 1992	.477	.56	2.34	.291	.806	.266	2.29	.246	-.019
TRK[#,2]	21 / 27	1526 - 1978	.527	.53	2.44	.248	.737	.267	2.47	.290	-.005
UWR[*,1]	38 (14) / 68 (29)	1140 - 1992	.593	.55	2.44	.266	.805	.256	2.24	.275	-.012
WBF	(15 / 31)	1674 - 1992	.556	.98	3.51	.374	.719	.216	2.37	.313	-.011

Note: * updated sites; # non-updated sites; 1 LaMarche *et al.* (1979a); 2 Norton (1983a). Refer to the text for more explanation.

(1979a) and Norton (1983a). The 5 updated sites include the data series measured by the original authors (LaMarche *et al.* 1979a) and the new data series made by this thesis. Based on each segments correlation with the Master Dating Series, some cores were rejected from several sites. In all updated sites, the new cores had a very high correlation with the original data series.

3.4 Standardisation

3.4.1 Introduction

The process of removing the effects of increasing tree size and age, random tree specific effects, the results of genetic, injury or of the tree's particular situation, or a combination of these and other localised effects, are called standardisation (Fritts, 1976).

The standardisation process has two objectives: (1) to remove non-climatic effects from every ring-width series and (2) to allow the resultant standardised values of individual trees to be averaged together into a mean-value function by adjusting the series for differential growth rates due to differing tree ages and differences in the overall rate of growth (Cook & Briffa, 1990). This is accomplished by dividing each measured ring width by its expected value, as estimated by G_t. That is,

$$I_t=R_t/G_t \qquad (3.1)$$

where I_t is the relative tree-ring index, R_t is the observed ring-width series and G_t is a function of the age trend component, endogenous and exogenous effects etc. R_t could be given by:

$$R_t = A_t + C_t + \delta D1_t + \delta D2_t + E_t \qquad (3.2)$$

where A_t is the age-size related trend in ring-width; C_t is the climatically related environmental signal; $D1_t$ is the disturbance pulse caused by a local endogenous disturbance; $D2_t$ is the disturbance pulse caused by a stand wide exogenous disturbance; and E_t is the largely unexplained year-to-year variability not related to the other signals. The δ associated with $D1_t$ and $D2_t$ is a binary indicator of the presence ($\delta = 1$) or absence ($\delta = 0$) of either class of disturbance in the ring-widths.

Thus, A_t, C_t, and E_t are assumed to be continuously present in R_t while $D1_t$ and $D2_t$ may or may not be present depending on whether or not the intervention of a disturbance has occurred at some time in the past 't' (Cook, 1987).

G_t is a function of A_t, $D1_t$, $D2_t$ and E_t. The process to estimate G_t is called detrending which is intended to remove overall trends in tree-ring measurement series. Detrending causes the time series characteristics of the various measurement series to be more similar to each other, and prepares them for subsequent autoregressive modelling. Fritts (1976) discusses the concept and reasons for detrending tree-ring series. Further discussion is given by Holmes *et al.* (1986), Briffa (1984), Murphy & Palmer (1992). Several methods have been employed to estimate G_t. The methods can be classed into two general types: deterministic and stochastic.

Deterministic methods typically involve fitting *a priori* defined mathematical models, such as linear regression, negative exponential curve or polynomial detrending methods. The linear regression and negative exponential method clearly require that the observed growth trend be simple in form because they only depend on time for predictive purposes. They are most appropriate for open-canopy stands of undisturbed trees and for young trees with strong juvenile age trends (Cook & Briffa, 1990). The polynomial growth-trend estimation is far more *ad hoc* (i. e. random) and data adaptive than the previous models. With polynomial standardisation, a best-fit, order-p polynomial (which is initially unknown), is fit to a ring-width series based on the behaviour of that series alone. However, this approach still maintains its dependence on time alone for predictive purposes. The weakness of the deterministic methods are: (1) in the real world, there are very few age trends known to have a simple deterministic form; (2) because of time-dependent stochastic departures from the theoretical model, noise-related medium-frequency variance may be retained in some parts of the series, yet removed in others.

Stochastic methods include low-pass digital filtering, exponential smoothing and differencing. They are designed to fit low- and middle-frequency stochastic perturbations commonly found in ring-width series. Low-pass digital filtering typically involves passing an odd-numbered set of symmetrical, low-pass filter weights over a ring-width series to produce a smoothed estimate of the actual series (Cook & Briffa, 1990). There are two different filtering methods: the smoothing spline (Cook & Peter, 1981) and the Gaussian response curve (Briffa, 1984). The smoothing spline can be thought of as a concatenation of cubic polynomial segments that are joined together at their ends or "knots" (Wold, 1974). The continuity of the first and second derivatives assures that the segments are joined in a very smooth fashion. In this sense, the smoothing spline is a series of piecewise cubic polynomials with a knot at each data point abscissa (Cook & Peters, 1981). The Gaussian response curve developed by Briffa (1984) is simply a type of weighted moving average. In practice, the smoothing spline and Gaussian filter are very similar (Briffa & Jones, 1990). Here, only a cubic smoothing spline is introduced in detail and most of the discussion will be focused on the program ARSTAN (Cook, 1985).

The cubic smoothing spline involves passing an odd-numbered set of symmetrical, low-pass filter weights over a ring-width series to produce a smoothed estimate of the actual series (Cook *et al.* 1990). This is accomplished as

$$G_t = \sum_{i=-n}^{+n} w_i R_{t+i} / \sum_{i=-n}^{+n} w_i \qquad (3.3)$$

where G_t is the *t*th filtered value and where w_i is the weight by which the value of the series i units removed from t is multiplied. There are 2n+1 filter weights. R_{t+1} is the observed ring-width in year t+1. The degree of smoothness of the low-pass filter estimates of G_t depends on the characteristic frequency response of the filter. The frequency-response function is computed as

$$\mu(f) = 1 - \frac{1}{1 + \dfrac{\rho(\cos 2\pi f + 2)}{6(\cos 2\pi f - 1)^2}} \qquad (3.4)$$

where ρ is the Lagrange multiplier that uniquely defines the frequency response of the spline. The 50% frequency-response cutoff, which is the frequency at which 50% of the amplitude of a signal is retained (or removed), is typically used to define the degree of smoothing by a digital filter. It can be defined in terms of ρ as

$$\rho = \frac{6(\cos 2\pi f - 1)^2}{\cos 2\pi f + 2} \qquad (3.5)$$

The amount of variance to be removed at a particular frequenc can be precisely specified; it will remove variance of lower frequencies (longer wavelengths) with a transition to little or no removal of variance of higher frequencies (shorter wavelengths). Thus its flexibility can be exactly specified and is almost infinitely adjustable (Cook and Peters, 1981).

Once a collection of ring-width series has been detrended and indexed into a new ensemble of tree-ring indices, the estimation of the common signal, C_t, can proceed. Two methods are included in ARSTAN: the arithmetic mean and the biweight robust mean that discounts outliers. The arithmetic mean is the classical method of estimating C_t, and is calculated by averaging the ensemble of detrended tree-ring indices across series for each year using the arithmetic mean (Fritts, 1976). If there are suspected outliers, or extreme values, in the tree-ring indices, than a robust mean such as the biweight mean (Mosteller & Tukey, 1977) can be used in place of the arithmetic mean. The use of a robust mean tacitly admits the likelihood of contamination by endogenous disturbance effects (like gap-phase stand dynamics) and other sources of noise having long-tailed, non normally distributed properties. Endogenous disturbance effects are likely to act as outliers because, as defined earlier, such disturbances tend to behave as random events in space and time. The biweight mean for year t is computed by iteration as:

$$\bar{I}_t = \sum_{j=1}^{m} w_t I_t \qquad (3.6)$$

$$w_t = \left(1 - \left(\frac{I_t - \bar{I}_t}{c\,S_t} \right)^2 \right)^2 \qquad (3.7)$$

where w_t is weight function. S_t is a robust measure of the standard deviation of the frequency distribution. I_t is the relative tree-ring index [(see Cook *et al.* (1990) for further details)].

3.4.2 The comparison of different detrending methods

A) Introduction

A major step in dendroclimatology is the standardisation of the raw ring-width series. The type of standardisation used is dependent on the nature of the raw series. Twelve data series were randomly selected from two sites (CLW and RUH) and plotted in Figure 3.6. This figure demonstrates the diverse range of trends seen in *Libocedrus bidwillii*. Here, every series has a different behaviour. The complexity of the series suggested the need for a two-stage process of detrending to solve the problem. First was the fitting of a negative exponential curve or just a horizontal line (no detrending), then fitting to the resulting indices a cubic spline and again calculating the indices.

The program ARSTAN was developed by Cook (1985) and includes several concepts not previously applied to tree-ring chronology development. ARSTAN is similar to other programs in that it produces chronologies from tree-ring measurement series by detrending and indexing (standardising) the series. There are several detrending options and two averaging methods included in ARSTAN. Figure 3.7 shows the different detrending methods applied to the same data series (CLW6-3) using ARSTAN.

In this comparison of different detrending methods, the following types were compared:

- ERH - negative-Exponential or linear Regression or a Horizontal detrending
- SP40 - spline detrending using ρ equivalent to 40 years (the 50% frequency-response cutoff in 40 years, see Equations 3.4 & 3.5)
- SP80 - spline detrending using ρ equivalent to 80 years
- SP120 - spline detrending using ρ equivalent to 120 years
- SP67% - spline detrending with ρ set at 2/3 (67%n) the length of each series

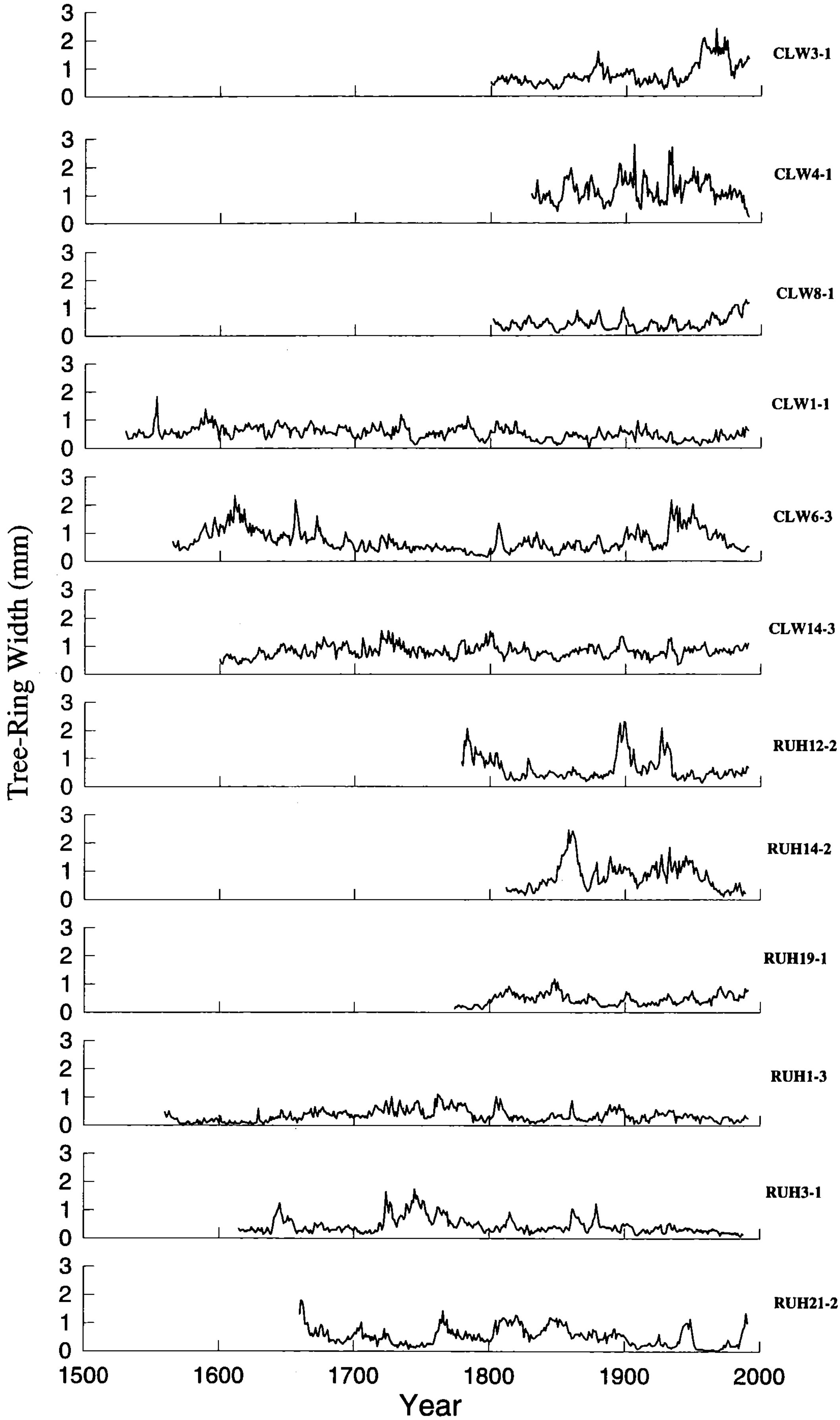


Figure 3.6 Examples of the trends seen in raw data series.

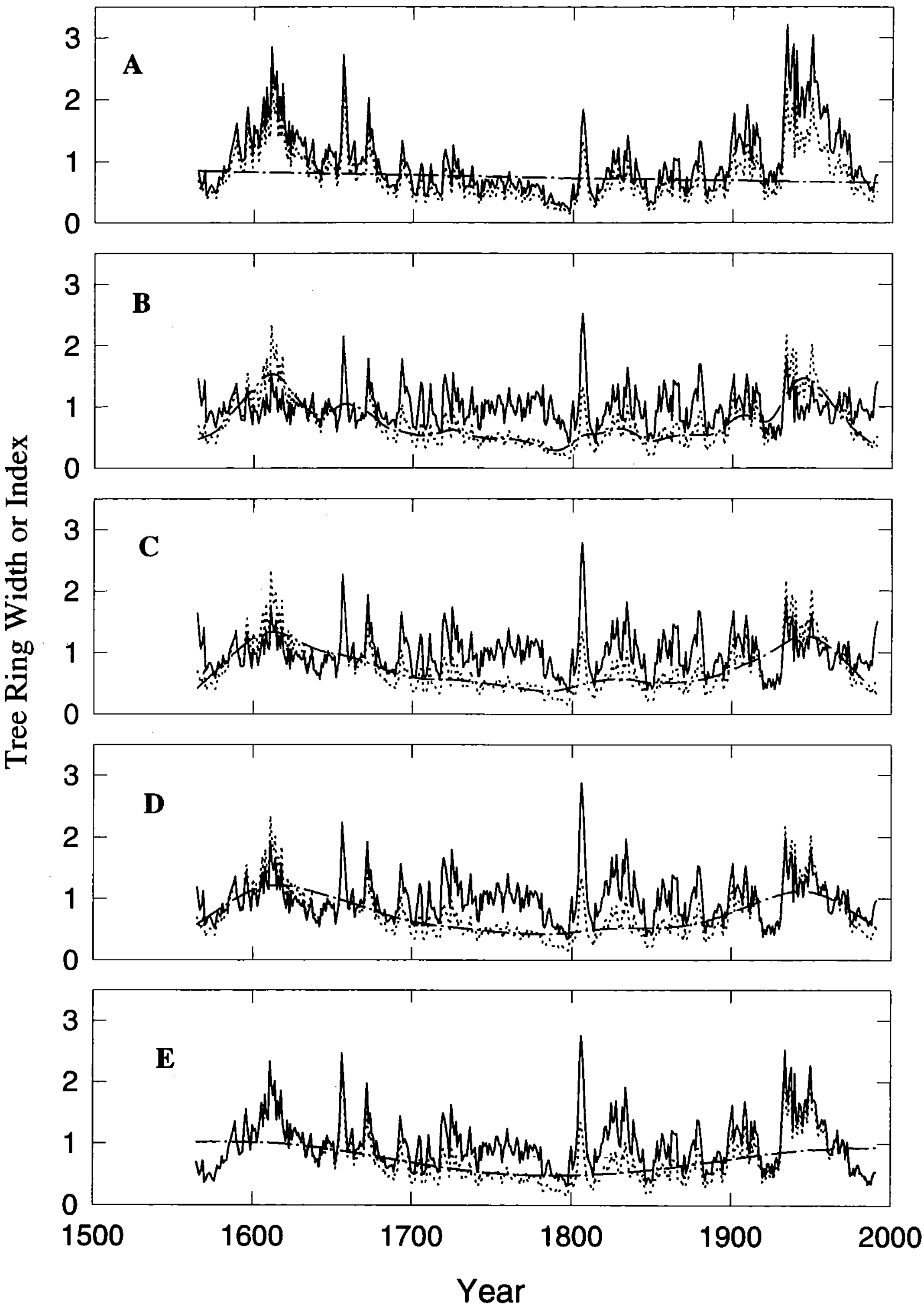


Figure 3.7 Comparison of different standardisation methods applied to one data series (CLW6-3). A. ERH B. SP40 C. SP80 D. SP120 E. SP67%. Refer to text for more explanation. ········ Ring Width, —— Ring Index, —·— Standardising curve.

The arithmetic mean and robust mean chronology were calculated separately on each data set. The results are discussed in two stages; the first step was to use single detrending on two sites (one from North Island and another from South Island) to compare the results of two chronology computation methods - arithmetic mean and robust mean (Table 3.4). Based on this, one chronology computation method was selected to compare single detrending and double detrending standardisation methods (Table 3.5).

B) Chronology computation methods

Table 3.4 Comparison of two chronology computation methods.

Statistics	Chronology with arithmetic mean					Chronology with robust mean				
	ERH	SP40	SP80	SP120	SP67%	ERH	SP40	SP80	SP120	SP67%
Site: CLW	Analysis period: 1802-1985 Span: 184 years					No. of trees: 16				
SD	.247	.179	.202	.213	.225	.250	.178	.199	.209	.223
VR	.061	.032	.041	.045	.051	.062	.032	.040	.044	.050
RV%						-2.4	1.11	2.95	3.72	7.24
Site: RUH	Analysis period: 1783-1950 Span: 168 years					No. of trees: 14				
SD	.276	.205	.244	.266	.425	.266	.199	.232	.254	.420
VR	.076	.042	.060	.071	.181	.071	.040	.054	.064	.176
RV%						7.12	5.77	9.59	8.82	2.34

Note:

SD: standard deviation; VR: variance; RV%: reduction in variance compared with the same detrending methods; ERH: linear-exponential curve or a linear regression line or a horizontal line; SP40, SP80, SP120, SP67%: 40, 80, 120 years and 67%n spline detrending.

Table 3.4 shows the summary statistics for the two sites and five detrending methods with different chronology mean computation methods. The results showed some reduction in error variance using the biweight mean (except ERH method in site CLW). This resulted in an average error variance reduction of about 2.54% (site CLW) and 6.73% (site RUH) in the robust mean-value functions compared with those based on the arithmetic mean. Site RUH was a more closed-canopy forest with more outlier tree-ring data than site CLW causing the observed differences in error variance reduction. Cook (1985) extensively used the biweight mean on closed-canopy forest tree-ring data and this revealed that approximately 45% of the yearly means of 66 tree-ring chronologies showed some reduction in error variance from using the biweight mean. There is about a 20% reduction in error variance when comparing robust means with arithmetic means. Because all 23 sites are more or less closed-canopy forests, only robust biweight means for chronology computations have been used.

C) Detrending methods

In order to compare the different detrending methods (different single detrending methods and double detrending methods), ten sites have been used for analysis. Nine detrending methods (5 single detrending methods, plus 4 double detrending methods) were performed on each data set. The five single detrending methods were: linear-Exponential curve or a linear Regression line or a Horizontal line (ERH); 40, 80, 120 years and 67%n spline detrending (SP40, SP80, SP120, SP67%); the four double detrending methods were: ERH plus different length of spline curve (Table 3.5). The ERH method tries to remove the overall growth trend. Most of the cores did not have a negative exponential growth trend, so the second and third options of ERH method were applied (I. e. a linear regression or just a horizontal line). The spline curve was used to remove low-frequency variance from each series.

The summary statistics (Table 3.5) used for comparing each of the standardisation methods were: mean sensitivity (MS), standard deviation (SD), coefficient of skew (SK), coefficient of kurtosis (KT), lag-1 autocorrelation coefficient (R1), average correlation among trees for the common overlap period among series (RBar), expressed population signal (EPS) and signal to noise ratio (SNR). The MS, SD, and R1 statistics are frequently used to assess the statistics of dendroclimatological quality of tree-ring chronologies (Fritts, 1976) and are not explained in detail here. MS measures the proportion of high-frequency variance and R1 measures the proportion of low-frequency variance. SD, however, is a measure of variations in both frequency domains. The SK and KT statistics are included to assess any higher-order effects on the probability distribution owing to the method of standardisation. EPS and SNR are also widely used to judge the "quality" of a chronology in recent

Table 3.5 Summary statistics for the standardisation methods.

Statistics	Single detrending					Double dedrending			
	ERH	SP40	SP80	SP120	SP67%	ERH+ SP40	ERH+ SP80	ERH+ SP120	ERH+ SP67%
Site: AHA Analysis period: 1772-1963 Span: 192 years No. of trees: 19									
MS	0.132	0.142	0.140	0.139	0.137	0.142	0.140	0.139	0.137
SD	0.271	0.201	0.211	0.213	0.210	0.201	0.211	0.213	0.210
R1	0.799	0.549	0.618	0.638	0.653	0.550	0.618	0.639	0.654
SK	0.109	0.101	0.560	0.330	-0.002	1.016	0.561	0.317	-0.024
KT	1.016	3.667	1.651	1.012	0.502	3.700	1.652	0.980	0.497
RBar	0.227	0.290	0.263	.254	0.250	0.291	0.263	0.254	0.250
EPS	0.848	0.886	0.872	0.866	0.863	0.886	0.872	0.886	0.863
SNR	5.577	7.768	6.782	6.461	6.316	7.786	6.784	6.467	6.323
Site: CLW Analysis period: 1802-1985 Span: 184 years No. of trees: 16									
MS	0.129	0.127	0.126	0.127	0.127	0.127	0.126	0.127	0.127
SD	0.250	0.178	0.199	0.209	0.223	0.178	0.200	0.209	0.223
R1	0.749	0.537	0.638	0.670	0.708	0.537	0.638	0.670	0.706
SK	0.618	0.421	0.489	0.530	0.571	0.420	0.494	0.537	0.569
KT	1.272	0.909	0.507	0.488	0.548	0.904	0.517	0.505	0.543
RBar	0.244	0.332	0.308	0.299	0.282	0.332	0.308	0.298	0.282
EPS	0.838	0.888	0.877	0.872	0.862	0.889	0.877	0.872	0.863
SNR	5.159	7.968	7.128	6.810	6.271	7.970	7.129	6.808	6.275
Site: MOA Analysis period: 1655-1975 Span: 321 years No. of trees: 16									
MS	0.118	0.124	0.126	0.126	0.127	0.124	0.126	0.126	0.127
SD	0.270	0.162	0.177	0.187	0.211	0.162	0.177	0.187	0.211
R1	0.842	0.484	0.570	0.626	0.713	0.484	0.571	0.625	0.714
SK	-0.349	0.240	-0.006	0.033	0.328	0.236	-.006	0.039	0.356
KT	-0.020	0.994	0.288	0.096	0.626	0.997	0.283	0.095	0.716
RBar	0.198	0.309	0.253	0.227	0.198	0.310	0.254	0.228	0.201
EPS	0.798	0.878	0.844	0.825	0.798	0.878	0.845	0.825	0.801
SNR	3.958	7.170	5.430	4.701	3.954	7.173	5.447	4.728	4.013
Site: NET Analysis period: 1757-1972 Span: 216 years No. of trees: 26									
MS	0.146	0.146	0.147	0.146	0.144	0.146	0.147	0.146	0.144
SD	0.215	0.166	0.178	0.183	0.185	0.166	0.178	0.184	0.186
R1	0.618	0.360	0.434	0.471	0.510	0.340	0.433	0.470	0.511
SK	0.334	0.063	0.189	0.128	-0.036	0.067	0.205	0.164	-0.014
KT	1.130	0.648	0.871	0.657	0.331	0.661	0.964	0.792	0.423
RBar	0.279	0.362	0.339	0.330	0.315	0.362	0.338	0.330	0.316
EPS	0.910	0.937	0.930	0.927	0.923	0.936	0.930	0.928	0.923
SNR	10.056	14.75	13.311	12.792	11.964	14.74	13.30	12.82	12.03

Table 3.5 (continued)

Statistics	Single dedrending					Double detrending			
	ERH	SP40	SP80	SP120	SP67%	ERH+ SP40	ERH+ SP80	ERH+ SP120	ERH+ SP67%
Site: RUC Analysis period: 1762-1960 Span: 199 years No. of trees: 24									
MS	0.123	0.123	0.124	0.123	0.123	0.123	0.124	0.123	0.123
SD	0.213	0.177	0.189	0.193	0.204	0.177	0.189	0.193	0.205
R1	0.694	0.538	0.602	0.631	0.677	0.537	0.601	0.631	0.678
SK	0.272	0.753	0.629	0.467	0.170	0.754	0.630	0.469	0.163
KT	0.913	2.326	1.886	1.452	1.287	2.325	1.876	1.436	1.335
RBar	0.275	0.337	0.314	0.300	0.287	0.337	0.314	0.300	0.287
EPS	0.901	0.924	0.917	0.912	0.906	0.924	0.917	0.911	0.906
SNR	9.085	12.20	10.985	10.303	9.643	12.20	10.98	10.30	9.638
Site: RUH Analysis period: 1783-1950 Span: 168 years No. of trees: 14									
MS	0.147	0.152	0.156	0.155	0.159	0.152	0.156	0.155	0.159
SD	0.266	0.199	0.232	0.254	0.420	0.199	0.232	0.253	0.420
R1	0.729	0.496	0.578	0.624	0.733	0.496	0.578	0.623	0.733
SK	0.148	-.085	0.249	0.829	5.012	-0.08	0.252	0.834	5.015
KT	0.506	1.010	1.716	3.789	37.296	1.006	1.719	3.816	37.31
RBar	0.218	0.306	0.296	0.281	0.261	0.306	0.297	0.282	0.262
EPS	0.796	0.861	0.855	0.846	0.832	0.861	0.855	0.846	0.833
SNR	3.892	6.180	5.898	5.474	4.953	6.184	5.915	5.510	4.976
Site: TKP Analysis period: 1721-1903 Span: 183 years No. of trees: 25									
MS	0.137	0.133	0.135	0.136	0.135	0.132	0.134	0.136	0.135
SD	0.292	0.187	0.215	0.233	0.254	0.187	0.215	0.234	0.253
R1	0.815	0.590	0.688	0.733	0.771	0.590	0.689	0.734	0.770
SK	0.714	-.038	0.141	0.243	0.385	-.039	0.144	0.245	0.378
KT	0.729	0.053	0.004	-0.066	0.025	0.055	0.003	-.076	0.014
RBar	0.323	0.375	0.349	0.362	0.357	0.375	0.350	0.363	0.358
EPS	0.923	0.937	0.931	0.934	0.933	0.938	0.931	0.934	0.933
SNR	11.954	14.98	13.429	14.157	13.851	15.03	13.49	14.24	13.92
Site: TOA Analysis period: 1750-1987 Span: 238 years No. of trees: 18									
MS	0.127	0.132	0.132	0.132	0.130	0.132	0.132	0.132	0.130
SD	0.229	0.168	0.186	0.194	0.197	0.168	0.186	0.197	0.197
R1	0.726	0.492	0.570	0.591	0.625	0.492	0.570	0.591	0.624
SK	0.427	0.379	0.604	0.633	0.550	0.378	0.605	0.635	0.542
KT	0.630	0.622	1.243	1.309	1.134	0.621	1.246	1.308	1.103
RBar	0.273	0.342	0.330	0.317	0.298	0.342	0.330	0.317	0.298
EPS	0.871	0.904	0.898	0.893	0.884	0.904	0.898	0.893	0.884
SNR	6.748	9.371	8.849	8.356	7.639	9.367	8.850	8.368	7.648

Table 3.5 (continued)

Statistics	Single detrending					Double detrending			
	ERH	SP40	SP80	SP120	SP67%	ERH+ SP40	ERH+ SP80	ERH+ SP120	ERH+ SP67%
Site: UWR Analysis period: 1507-1740 Span: 234 years No. of trees: 18									
MS	0.167	0.169	0.169	0.169	0.171	0.169	0.169	0.169	0.171
SD	0.250	0.215	0.234	0.240	0.246	0.215	0.234	0.240	0.247
R1	0.644	0.476	0.558	0.582	0.604	0.476	0.558	0.582	0.605
SK	0.412	0.489	0.586	0.591	0.540	0.489	0.585	0.592	0.540
KT	1.065	1.984	1.956	1.766	1.469	1.987	1.955	1.766	1.459
RBar	0.202	0.355	0.313	0.288	0.233	0.355	0.313	0.288	0.233
EPS	0.820	0.908	0.892	0.879	0.845	0.908	0.891	0.879	0.845
SNR	4.547	9.895	8.219	7.278	5.460	9.894	8.216	7.280	5.471
Site: WBF Analysis period: 1860-1992 Span: 133 years No. of trees: 14									
MS	0.127	0.141	0.142	0.142	0.140	0.141	0.142	0.142	0.141
SD	0.316	0.169	0.197	0.238	0.234	0.169	0.197	0.238	0.234
R1	0.865	0.414	0.545	0.653	0.668	0.414	0.545	0.654	0.667
SK	-0.652	0.092	0.536	1.370	0.895	0.093	0.536	1.368	0.901
KT	0.612	1.852	2.428	4.988	3.819	1.854	2.428	4.984	3.843
RBar	0.313	0.374	0.365	0.355	0.350	0.374	0.365	0.356	0.350
EPS	0.865	0.893	0.889	0.885	0.883	0.893	0.889	0.885	0.883
SNR	6.385	8.361	8.032	7.722	7.532	8.369	8.032	7.730	7.541

studies (Wigley *et al.* 1984; Briffa, 1984; Palmer, 1989; Briffa & Jones, 1990; Cook & Briffa, 1990; Murphy & Palmer, 1992). EPS is often used to estimate chronology confidence and provides an estimate of the strength of the common signal in the chronology. A value of 0.85 is one reasonable choice suggested by Briffa (1984). But no specific value of EPS can be thought of as adequate or a minimum to ensure that a chronology is suitable for climate reconstruction. SNR is mathematically related to EPS. Since the SNR has no upper limit, its general use in comparing statistical qualities between "different" chronologies has been noted as problematic (Briffa, 1984). However, in this section, it is only used to compare the different detrending methods applied on the same chronology.

Table 3.5 shows the summary statistics for the ten sites and nine standardisation methods. It is readily apparent that most of the statistics are extremely similar regardless of the method of standardisation. The ERH method has the lowest EPS and SNR value. The double detrending (ERH + different spline length) methods always increased EPS and SNR values. EPS and SNR decreased from SP40 (or ERH+SP40 in double detrending) to SP67% (or ERH+SP67% in double detrending). MS reflects the high frequency retained in the chronology. ERH methods had the lowest MS but all other spline methods or double detrending methods nearly had no differences in MS value. Differences in R1 reflect how much low-frequency variances has been removed by each method. The ERH method generally removes the least; the SP40 or ERH+SP40 method, defined by the 50% cutoff, removes the most. The way in which this low-frequency variance removal translates into the estimates of RBar is predictable. The RBar decreases from SP40 (or ERH+SP40) to SP67% (or ERH+SP67%). ERH methods had the lowest RBar value. These similar performances reflect the similarity in the low-frequency properties of the raw data in all ten sites. Overall, when the same length of spline methods was used, double detrending increased SNR but resulted in little changes for other parameters.

D) The correlations between chronologies developed by different standardisation methods

Apart from the summary statistics discussed in the previous section (section B), the correlations among the chronologies developed by the different standardisation methods was also examined (Table 3.6).

The correlations between chronologies as a function of the standardisation method are shown in Table 3.6. The correlations are usually high and often greater than 0.90. While some are quite low, e.g., 0.582 (ERH+SP40 versus ERH+SP67%) for site RUH and 0.728 (ERH+SP40 versus ERH+SP67%) for site WBF, all of them are significant at the 1% level. The greatest differences are found between the ERH+SP67% and ERH+SP40 methods. ERH+SP40, ERH+SP80 and ERH+SP120 are very similar but ERH+SP120 are closer to ERH+SP67%. There are only two sites (RUH and UWR) where correlations between ERH+SP120 and ERH+SP67% are below 0.95. These differences largely reflect how much low-frequency variance was left in the final chronology by each standardisation method. This fact is graphically revealed in the variance spectra of the different chronologies and is discussed in the next section.

Table 3.6. Correlations of the chronologies of each site developed by four double detrending standardisation methods.

	ERH+ SP40	ERH+ SP80	ERH+ SP120	ERH+ SP67%	ERH+ SP40	ERH+ SP80	ERH+ SP120	ERH+ SP67%
	Site: AHA				Site: CLW			
ERH+SP40	1.000	0.960	0.932	0.894	1.000	0.949	0.913	0.875
ERH+SP80		1.000	0.990	0.951		1.000	0.989	0.958
ERH+SP120			1.000	0.969			1.000	0.978
ERH+SP67%				1.000				1.000
	Site: MOA				Site: NET			
ERH+SP40	1.000	0.944	0.876	0.760	1.000	0.973	0.943	0.902
ERH+SP80		1.000	0.978	0.895		1.000	0.986	0.942
ERH+SP120			1.000	0.958			1.000	0.972
ERH+SP67%				1.000				1.000
	Site: RUC				Site: RUH			
ERH+SP40	1.000	0.977	0.946	0.881	1.000	0.950	0.883	0.582
ERH+SP80		1.000	0.988	0.930		1.000	0.974	0.721
ERH+SP120			1.000	0.965			1.000	0.837
ERH+SP67%				1.000				1.000
	Site: TKP				Site: TOA			
ERH+SP40	1.000	0.949	0.882	0.816	1.000	0.964	0.928	0.892
ERH+SP80		1.000	0.977	0.927		1.000	0.989	0.955
ERH+SP120			1.000	0.977			1.000	0.974
ERH+SP67%				1.000				1.000
	Site: UWR				Site: WBF			
ERH+SP40	1.000	0.925	0.904	0.827	1.000	0.889	0.737	0.728
ERH+SP80		1.000	0.993	0.924		1.000	0.942	0.933
ERH+SP120			1.000	0.935			1.000	0.984
ERH+SP67%				1.000				1.000

E) Spectral analysis of chronologies developed by different standardisation methods

Power spectrum analysis is designed for the study of rhythmic behaviour in a time series. If the variances in the time series are purely random, the spectrum will approximate a horizontal line (i. e. all spectral estimates are the same for all frequencies; Mitchell *et al.*, 1966). In such a situation, the variance in the time series is about equally distributed at all frequencies, and the spectrum is called a "white noise" spectrum by analogy to the properties of white light (LaMarche, 1974). If a time series is a pure sine wave, the spectrum will contain a relatively sharp peak at the appropriate frequency for the sine wave. If there is a regular periodicity having a nonsinusoidal shape, the spectrum will contain not only a peak at the basic wavelength, but other peaks at wavelengths corresponding to one or more higher harmonics of its basic wavelength. If there is a quasi-periodicity, or irregular rhythm, the spectrum will express it as a relatively broad hump spanning an appropriately wide range of wavelengths. Persistence in a time series (the tendency for large values to follow large values or small values to follow small values) cause a "reddening" of the spectrum; again, the term is used by analogy with light. A "red noise" spectrum has high spectral densities at low frequencies. Such persistence in a time series may reflect very low frequency oscillations, trends, or the influence of autoregressive or moving-average mechanisms that introduce a dependency on previous values in the series. The spectrum of a time series containing a strong sinusoidal periodic component will show a sharp peak at the frequency of the basic wave. A broader and less pronounced peak in the spectrum indicates the presence of a rhythmic or oscillatory component that is not exactly periodic, or of a periodic component showing phase shifts (LaMarche 1974).

Each spectrum is computed from 55 lags of the autocorrelation function and smoothed with the Hamming window (Guiot, 1995). The chronology power spectra in Figure 3.8 & 3.9 indicate that the four chronologies produced from different methods of each site are very similar at high frequencies from 0.06 to 0.5 cycles per year while the spectra at low frequencies (< 0.06 cycles per year) are very different. For

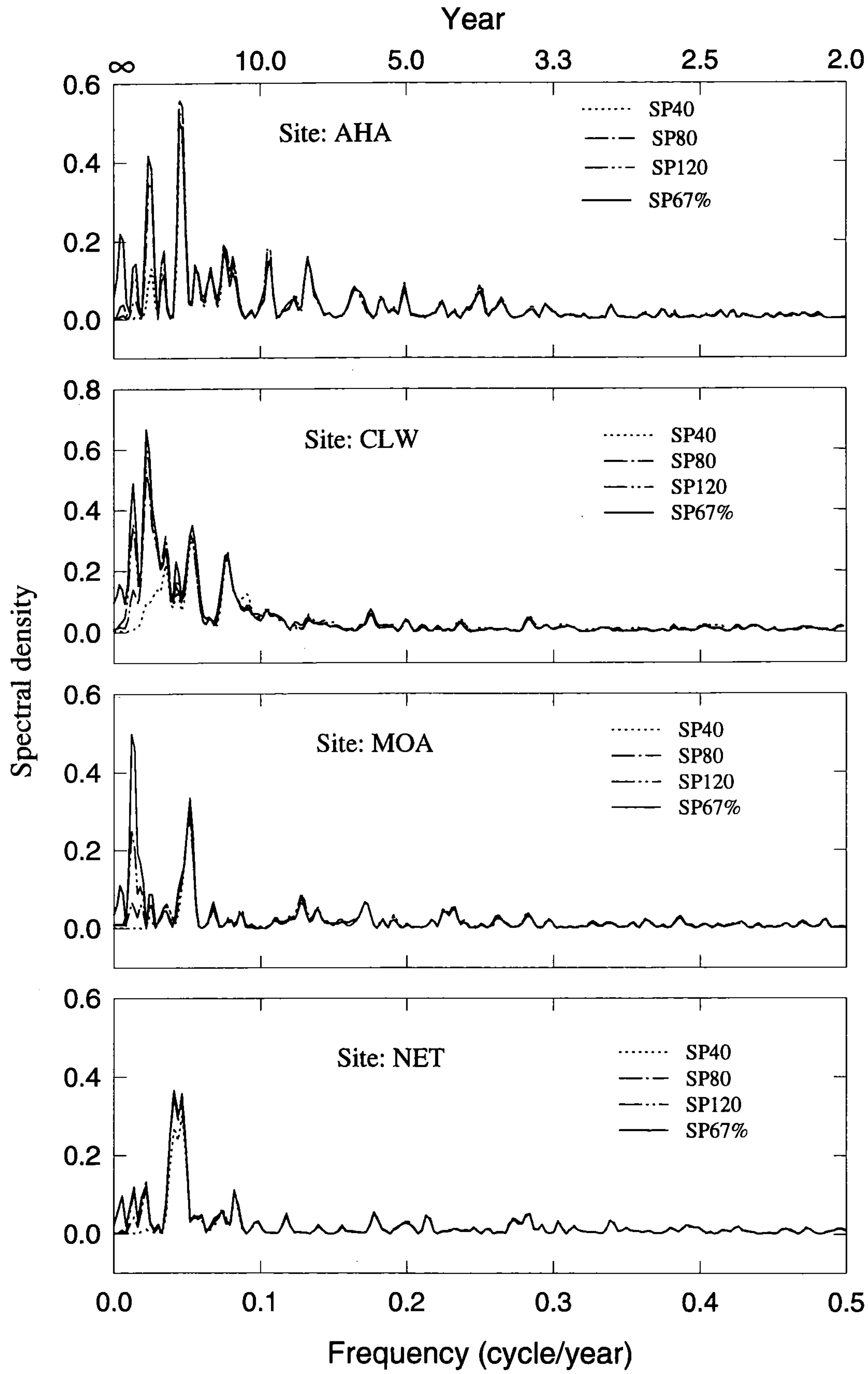


Figure 3.8A The comparison of spectral density of chronologies developed by different detrending methods (for sites AHA, CLW, MOA & NET).

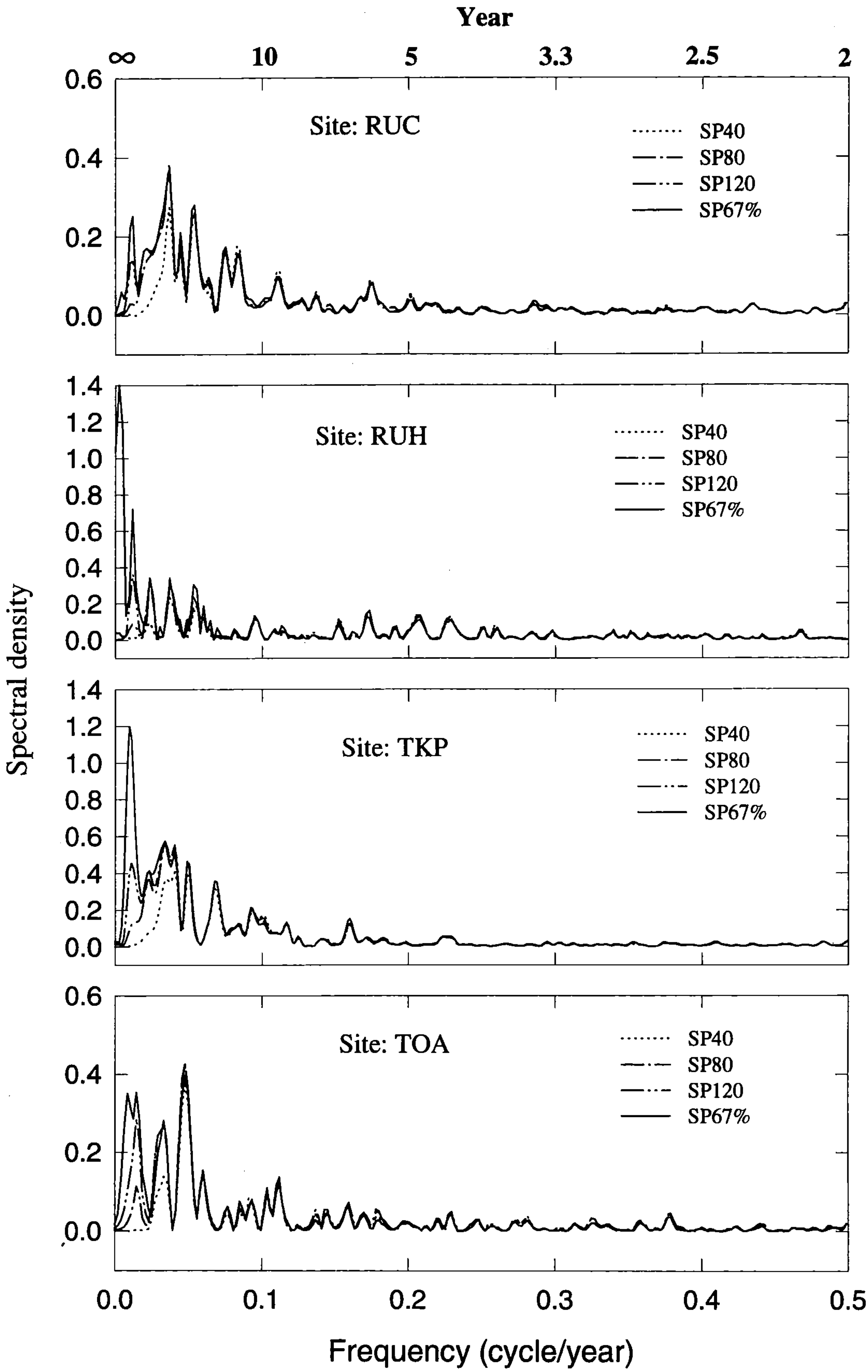


Figure 3.8B The comparison of spectral density of chronologies developed by different detrending methods (for sites RUC, RUH, TKP & TOA).

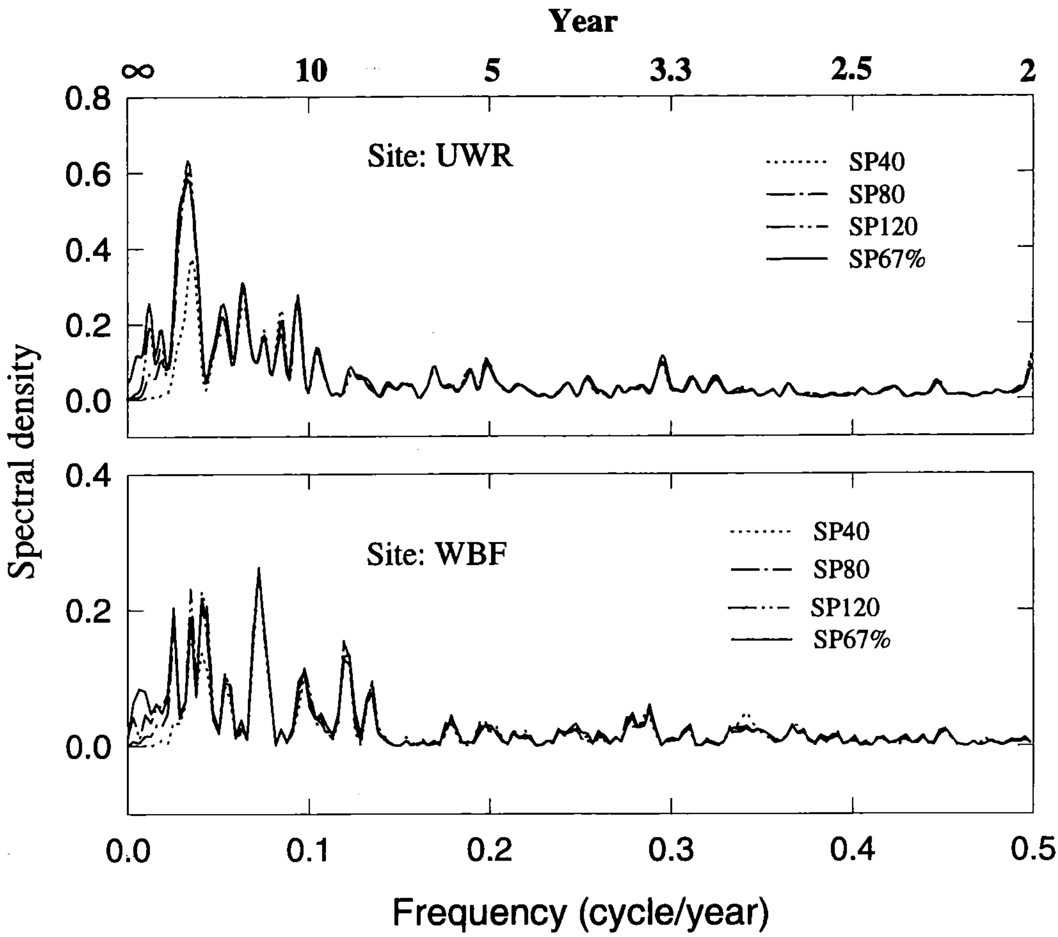


Figure 3.8C The comparison of spectral density of chronologies developed by different detrending methods (for sites UWR & WBF).

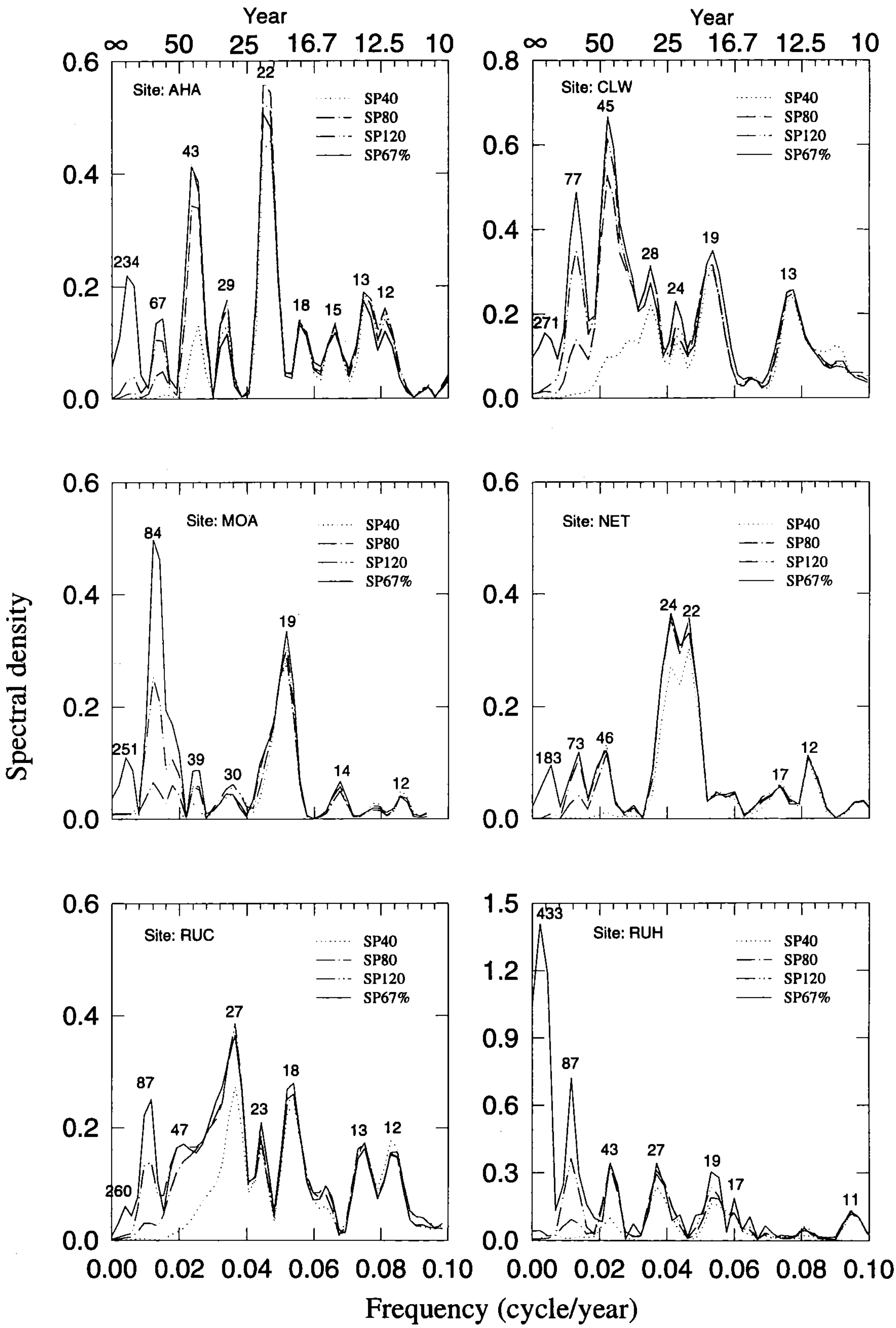


Figure 3.9A The enlarged low frequency bands of the spectral density of chronologies developed by different detrending methods (for sites AHA, CLW, MOA, NET, RUC & RUH).

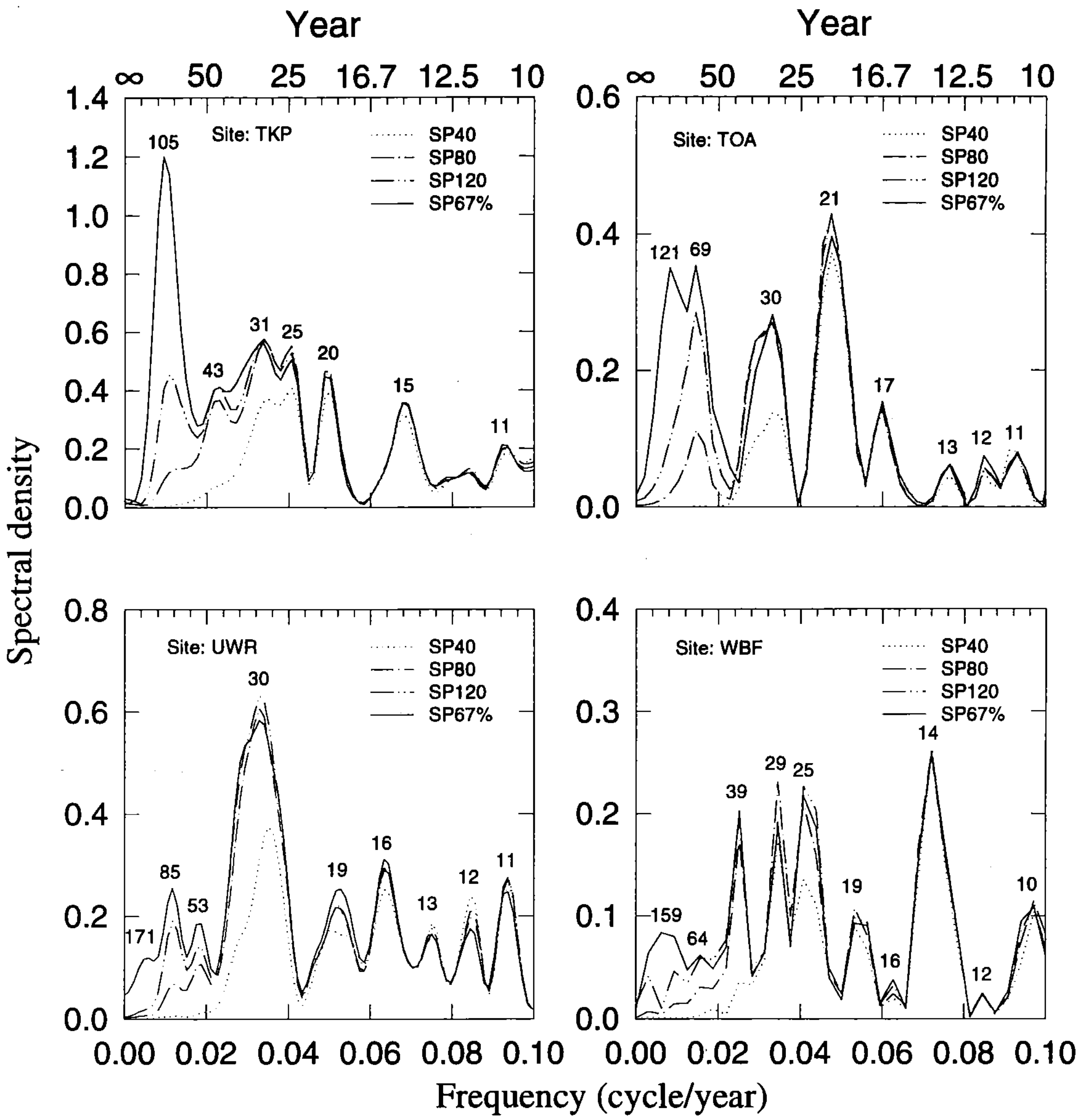


Figure 3.9B The enlarged low frequency bands of the spectral density of chronologies developed by different detrending methods (for sites TKP, TOA, UWR & WBF).

the different methods, the power spectrum at lower frequencies are always ERH+SP67% > ERH+SP120 > ERH+SP80 > ERH+SP40. There was the most number of peaks in the ERH+SP67% chronology which kept the greatest amount of low frequency and the least number of peaks in the ERH+SP40 chronology which kept the least amount of low frequency.

3.4.3 Climate consideration

Six climate data series were selected for spectral analysis on the basis of their representativeness, quality and length. One of these was the New Zealand average monthly temperature from 1853 to 1992 and average total monthly precipitation from 1888 to 1992. All the other series were mean monthly temperature and mean monthly precipitation from specific stations. The five sites included three from the North Island (a, b & c) and two from the South Island (d & e). The five sites were:

a. New Plymouth (C94001) which was close to chronology sites NET, EMT and STR.
b. Hiwi, Taihape (E95681) which was close to site HIT, CLW, OHT and RUC.
c. Onepoto, Waikaremoana (D87811) which was close to site UWR.
d. Nelson (G23231) which was near chronology sites MOA and FLG.
e. Hokitika South (F20791) which was on the west coast close to site AHA and RUH.

When missing data in some climate stations were encountered, estimations were obtained from the average of nearby climate sites of the same period. No climate sites were used if the missing data constituted more than 5%. The average growth season (Nov.-Mar.) temperature and total rainfall for this period were analysed. Maximum available length of record was used for each parameter.

From Figure 3.10, it is clear that the temperature patterns in all the six data series are similar. There are strong cycles in the low frequency band which is longer than 120 years. The rainfall pattern is very different, but normally has some low frequency cycles.

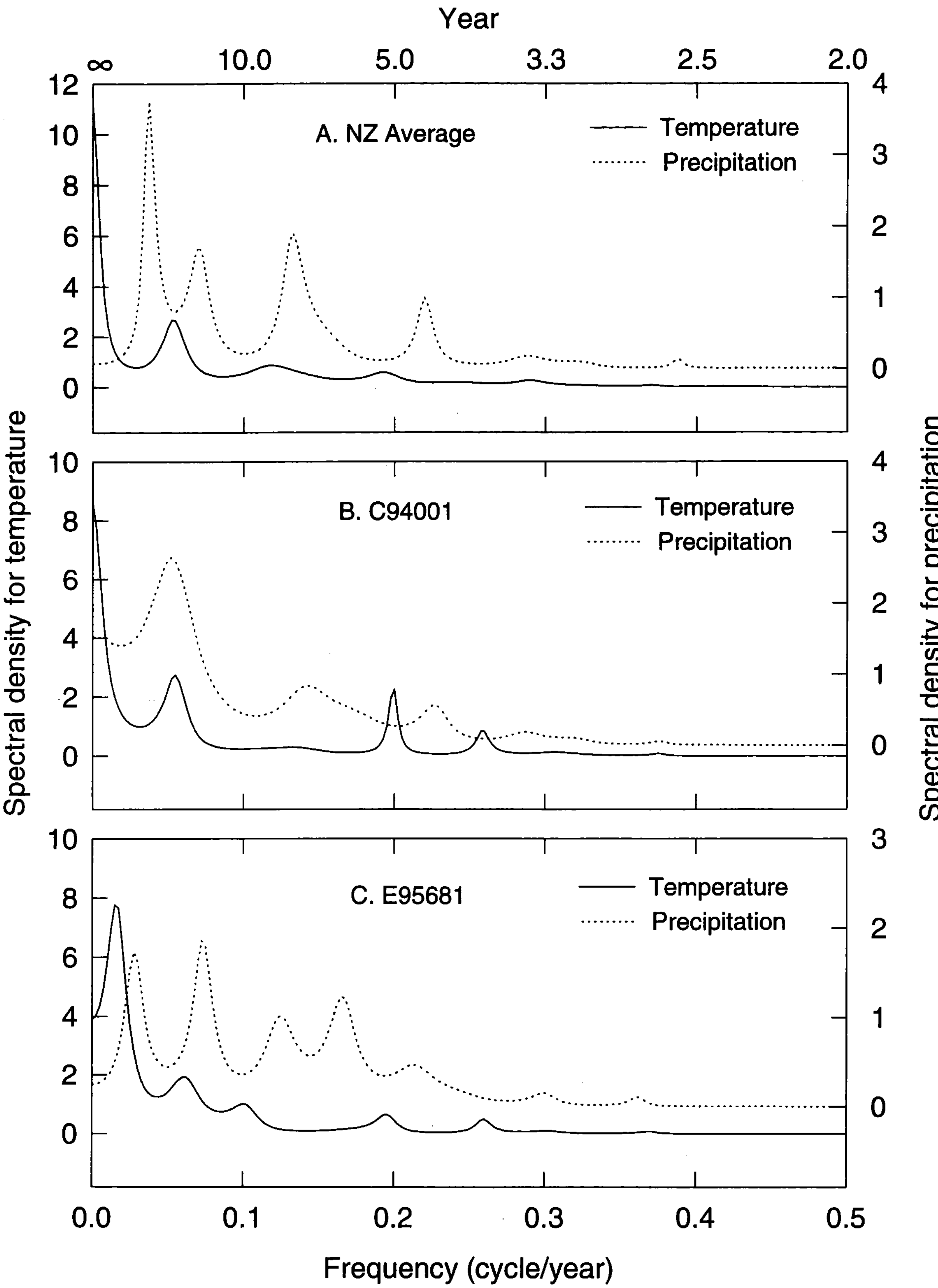


Figure 3.10A The spectral density of summer months (Nov.-Mar.) climate data for NZ Average, climate station C94001 and F20791. Refer to Chapter 5 for the code of the climate stations.

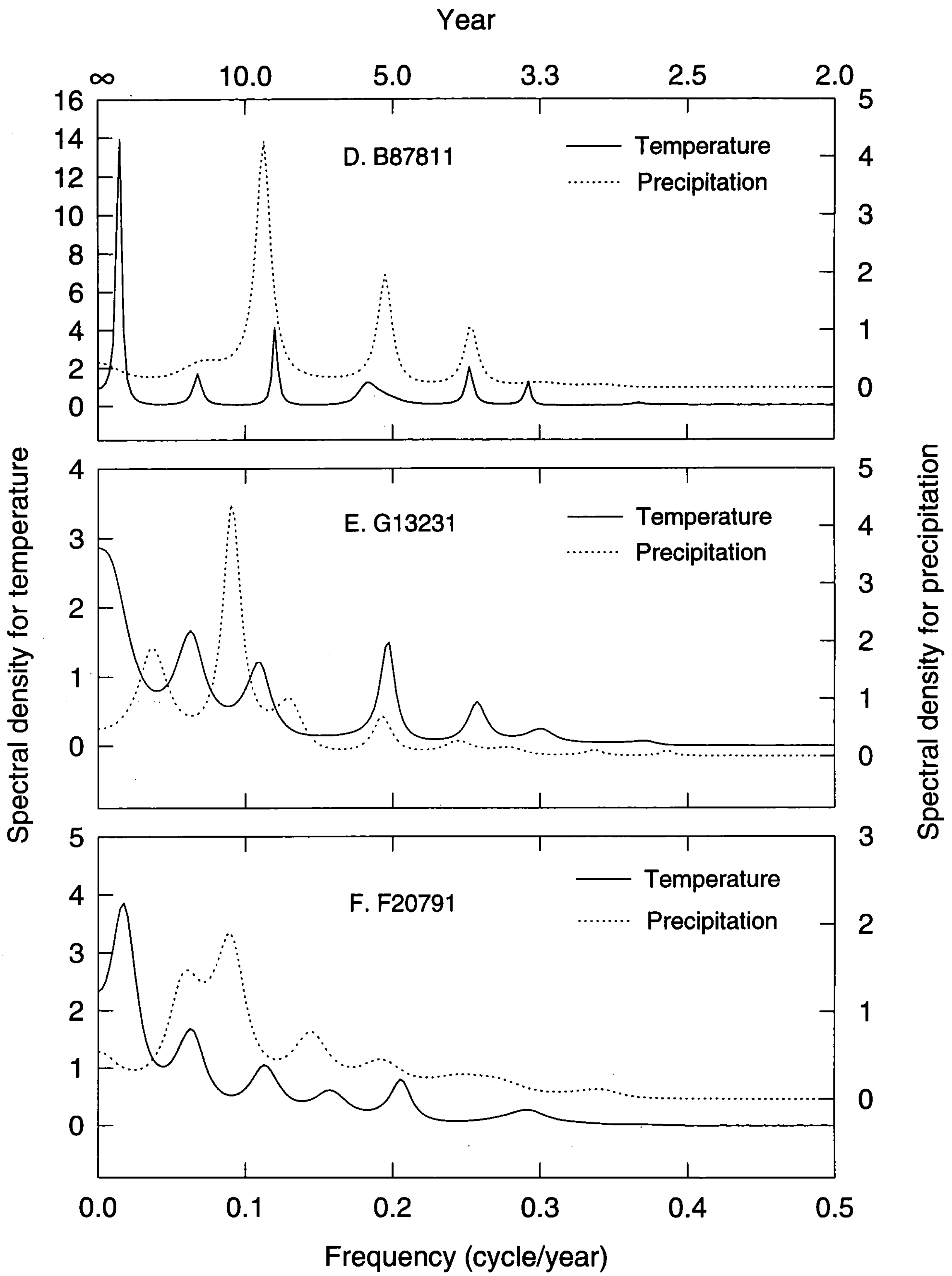


Figure 3.10B The spectral density of summer months (Nov.-Mar.) climate data for climate station D87811, G13231 and F20791. Refer to chapter 5 for the code of the cimate stations.

3.4.4 Conclusion

From the above discussion, it was clear that double detrending methods can increase SNR and the robust mean chronology computation method can decrease error variance. The double detrending method with robust mean computation should be selected. If so, which spline filter should be selected? Chronologies from ERH+SP40 had the highest SNR and also the highest MS. This means it kept more high frequency signals. The results of spectral analysis of chronologies which come from different detrending methods showed that all the four double detrending methods differed little at high frequency but large differences occurred at low frequency. Only the chronology using the ERH+SP67% method kept some low frequency signal longer than 120 years. The climate data spectral analysis suggests that some low frequency signals longer than 120 years appeared in the temperature and rainfall data. Because the initial objective was to reconstruct past temperature and rainfall, some low frequency signal in the final chronologies was considered important. As a result, double detrending methods (ERH+SP67%) and the robust mean computation method were selected for standardisation in this thesis. This standardisation approach resulted in a MS increase of 1.68%, EPS and SNR decrease of 2.9% and 22.3% respectively, compared with the ERH+40% method.

3.5 Autocorrelation

3.5.1 Introduction

The standardised tree-ring data often contain significant autocorrelations which violate the independence assumption necessary for most statistical analyses, and consequently bias hypothesis tests (e. g. analysis of variance). The problem has long been known (Fritts, 1976), but has often been ignored.

This section examines autocorrelation in the chronologies. The program ARSTAN was employed to remove the autocorrelation.

Table 3.7 Autocorrelation values in the standardised chronologies for ten selected sites (* p < 0.05; ** p < 0.01)

Lag	Chronology sites									Mean	SD
	AHA	CLW	MOA	NET	RUC	RUH	TKP	TOA	UWR	WBF		
1	0.653**	0.706**	0.714**	0.511**	0.678**	0.733**	0.770**	0.624**	0.685**	0.667**	0.674	0.067
2	0.402**	0.548**	0.560**	0.274**	0.466**	0.610**	0.617**	0.401**	0.535**	0.479**	0.489	0.102
3	0.254**	0.408**	0.484**	0.259**	0.309**	0.545**	0.476**	0.240**	0.446**	0.391**	0.381	0.104
4	0.156**	0.281**	0.403**	0.202**	0.185**	0.373**	0.355**	0.130**	0.268**	0.302**	0.266	0.090
5	0.049	0.191**	0.306**	0.062	0.103*	0.266**	0.259**	0.048	0.151**	0.198**	0.163	0.091
6	-0.019	0.116**	0.206**	-0.003	0.026	0.181**	0.194**	0.015	0.091**	0.112*	0.092	0.080
7	-0.031	0.062	0.149**	-0.070	-0.061	0.087	0.127**	-0.013	0.004	0.081	0.034	0.074
8	-0.055	0.006	0.111*	-0.088	0.122**	0.031	0.102*	0.036	-0.056	0.060	0.003	0.076
9	-0.039	-0.007	0.065	-0.102	0.144**	-0.031	0.086	0.058	-0.074*	-0.001	-0.017	0.071
10	-0.034	-0.016	0.038	-0.071	-0.111*	-0.068	0.081	0.052	-0.088*	0.008	-0.021	0.061
11	-0.018	-0.057	0.042	-0.078	-0.096*	-0.091	0.057	0.028	-.101**	0.026	-0.029	0.060
12	-0.010	-0.087	0.053	-0.089	-0.091*	-0.066	0.038	-0.010	-.094**	0.029	-0.033	0.056
13	-0.015	-0.097*	0.037	-0.070	-0.100*	-0.016	0.025	-0.049	-0.087*	0.021	-0.035	0.050
14	-0.053	-.117**	0.033	-0.046	-0.084	-0.002	-0.001	-0.069	-0.075*	0.001	-0.041	0.045
15	-0.052	-.128**	0.017	-0.042	-0.058	0.017	-0.040	-0.120*	-0.069	0.014	-0.046	0.049
16	-0.065	-0.109*	0.016	0.012	-0.000	0.048	-0.034	-0.069	-0.031	0.016	-0.022	0.046
17	-0.066	-0.098*	0.011	0.035	0.040	0.035	-0.013	-0.034	-0.046	-0.002	-0.014	0.044
18	-0.051	-0.082	-0.054	0.024	0.061	0.036	-0.005	0.023	-0.026	-0.046	-0.012	0.044
19	-0.008	-0.099*	-0.086	0.060	0.045	0.005	-0.012	0.022	-0.037	-0.063	-0.017	0.051
20	0.021	-0.099*	-0.093*	0.120*	0.040	-0.000	-0.016	0.002	-0.012	-0.090	-0.013	0.065
21	0.054	-0.072	-0.108*	0.086	0.052	-0.009	-0.015	-0.041	-0.025	-0.108	-0.019	0.064
22	0.060	-0.057	.154**	0.095	0.070	-0.037	-0.009	-0.048	-0.051	-0.122*	-0.025	0.077
23	0.068	-0.032	-.173**	0.125*	0.107*	-0.018	-0.012	-0.050	-0.039	-0.163**	-0.019	0.095
24	0.067	-0.038	-.222**	0.084	0.082	-0.033	-0.005	-0.053	-0.045	-0.184**	-0.035	0.098
25	0.045	-0.053	-.249**	0.042	0.014	-0.050	-0.011	-0.028	-0.071*	-0.157**	-0.052	0.087

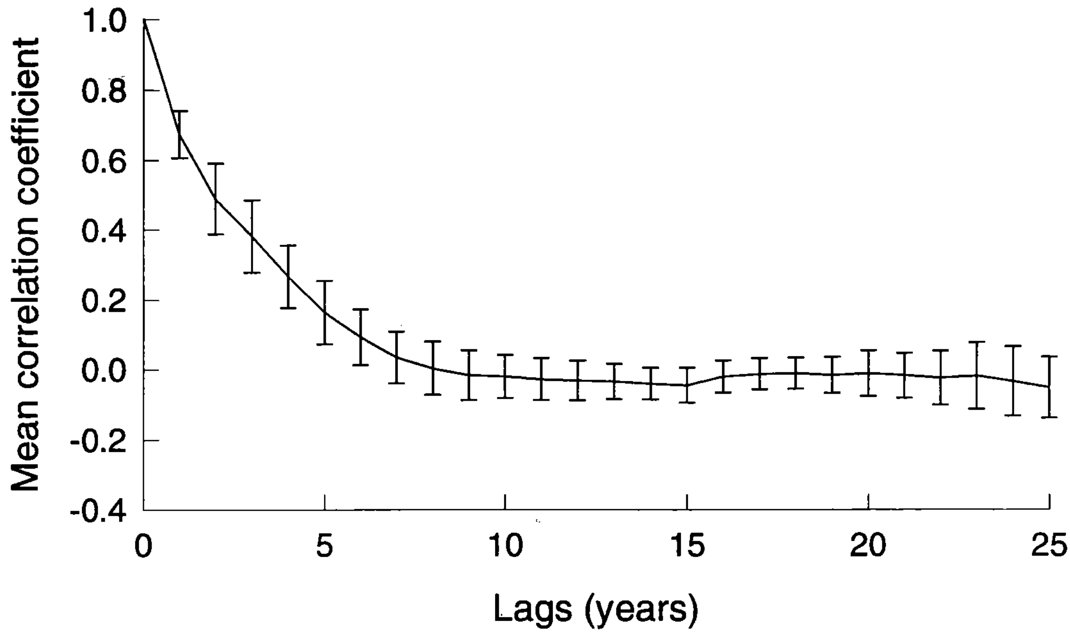


Figure 3.11 Mean lag pattern of 10 selected chronologies.

In order to investigate any pattern in the autocorrelation functions, the means were calculated at each lag (Table 3.7) and plotted (Figure 3.11) from the ten selected chronologies.

Table 3.7 shows that the number of significant lags varies considerably from site to site. The first four lags in all ten sites were positively significant (at 1% level). Such a pattern is commonly encountered and is generally simply explained as a carry-over effect of the former year (e.g. in years of favourable growth, excess sugars and hormones may contribute to growth in the following year, increasing the likelihood of a wide ring).

The fact that all the ten sites had significant autocorrelations indicated the need for its removal before any climate reconstruction was attempted.

3.5.2 Methods

In general, when using Auto-Regressive-Moving-Average or ARMA(p,q) models for chronologies, the order to set p and q is determined by a sequence of steps (Guiot, 1986). These have been simplified from the original methods explained by Box & Jenkins (1970). The first step is to look at the autocorrelation function and the partial autocorrelation function (which is simply the series of correlation coefficients of each lag, independent of the previous lags). If the autocorrelations decrease exponentially and the partial autocorrelations rapidly fall and become insignificant after p lags, use of an ARMA(p,0) model is called for. On the other hand, if the partial autocorrelations gradually decline and the standard autocorrelations rapidly fall after q lags, then an ARMA(0,q) model should be used.

Program ARSTAN has been used to remove the autocorrelations. Robust estimation of the mean value function produces a chronology with a strong common signal and without persistence (the STNDRD (standard) version). If modelling of the residual chronology reveals that there is an autoregressive process, the chronology is whitened by modelling the portion containing four or more series, and applying the model to the entire chronology. This produces the 'RESID' (residual) version. If the initial chronology is not an autoregressive process it is not modelled. The earliest date of the RESID version may be one or more years later than the STNDRD, depending on the order of the AR model and of the rewhitening process. Each series may be modelled as an autoregressive process where the order is selected for the individual series by first minimum Akaike Information Criterion (AIC) search. Univariate autoregressive modelling is performed, fitting an autoregressive process of the selected order to each series, and the following are computed for the residual series:

(a) Statistics for each series;
(b) Autoregressive coefficients for each series and the variance explained by autoregression;
(c) Normalised residuals which are outliers over three standard deviations from the mean.

Table 3.8 lists the sites and the types of ARMA(p,0) models fitted. It shows there are no significant autocorrelations left in any residual chronologies.

Apart from a residual chronology, ARSTAN also produces another kind of chronology. This third kind of chronology is produced using the 'RESID' chronology. The following are computed as before: (a) Lag-product sum matrices (b) Pooled lag-product sums (c) Pooled autocorrelations (d) Yule-Walker estimates of pooled autoregression (e) Akaike Information Criterion (AIC) and selected order of autoregression. If no significant multivariate persistence remains after the univariate fitting, the selected autoregression order is now zero. Using the autoregressive coefficients selected in the first multivariate autoregressive modelling in the above step, the pooled autoregression (persistence) model is reincorporated into the residual chronology to produce the 'ARSTAN' chronology. Statistics on the chronology include the distribution of yearly values and the autocorrelation structure. The pooled model of autoregression is added to the RESID version to produce the ARSTAN chronology. The pooled autoregression contains the common persistence and synchronous among a large proportion of series from the site, without including that found in only one or a very few series (Cook, 1985; Grissino-Mayer *et al.*, 1992). It is intended to contain the strongest climatic signal possible. The earliest date of the

ARSTAN chronology is usually the same year as the STNDRD, or if the RESID version required whitening.

Table 3.8 Autocorrelation values in the Residual chronologies for all 23 sites

Site	AR	Lags (year)									
	Model	1	2	3	4	5	6	7	8	9	10
ARM	2	0.005	0.050	0.015	0.056	0.034	-0.082	-0.061	-0.069	-0.086	-0.053
CRC	2	-0.027	-0.014	0.040	-0.055	0.041	0.005	-0.058	-0.012	-0.065	-0.012
CRG	1	0.021	0.005	0.040	0.014	0.058	-0.030	-0.069	-0.113	-0.039	0.082
OKA	1	-0.106	-0.112	0.082	0.123	-0.051	0.027	-0.015	-0.074	-0.090	-0.109
TRK	1	-0.056	-0.023	-0.061	-0.019	0.039	0.021	-0.023	-0.020	0.013	0.052
AHA	2	-0.109	-0.029	-0.020	0.047	-0.026	-0.072	0.027	-0.076	0.017	-0.031
EMT	6	-0.074	-0.001	0.120	-0.010	-0.087	-0.114	-0.087	0.013	-0.051	-0.037
MWO	3	-.130	-.029	-.047	.002	.076	.017	-.012	.036	-.015	.036
NET	1	-0.093	-0.112	0.063	0.094	-0.087	-0.016	-0.034	-0.012	-0.043	-0.020
TKP	2	-0.026	0.033	0.029	-0.002	-0.009	0.026	-0.055	-0.006	-0.016	0.063
UWR	1	-0.042	-0.034	0.005	0.048	-0.080	0.054	-0.053	-0.072	-0.050	0.040
CLW	1	-0.046	0.013	0.014	-0.025	-0.004	-0.032	0.007	-0.042	0.021	0.019
FLG	1	.004	-.024	.072	-.027	-.056	-.003	-.015	-.073	-.023	-.021
HIT	2	0.004	-0.046	0.002	0.042	-0.066	-0.071	-0.158	-0.044	-0.030	0.006
MOA	1	-0.019	-0.053	0.041	0.045	0.022	-0.033	-0.025	0.038	-0.052	-0.065
OHT	1	-0.084	0.032	-0.038	-0.080	-0.035	-0.055	-0.015	-0.045	0.026	-0.005
RUC	2	0.010	-0.025	-0.040	-0.055	0.000	0.017	-0.075	-0.077	-0.090	-0.008
RUH	1	0.017	-0.083	-0.009	0.002	0.095	0.037	-0.060	-0.056	-0.024	-0.084
STR	2	-0.018	0.059	0.077	-0.060	-0.047	0.029	-0.109	-0.001	0.041	0.037
TOA	1	-0.027	-0.041	0.006	-0.046	-0.031	0.017	-0.124	0.055	0.036	0.028
TOB	3	0.005	-0.047	0.018	0.022	-0.009	0.005	-0.110	-0.063	-0.020	0.064
TOC	2	-0.052	0.080	-0.023	-0.029	-0.077	-0.025	-0.083	-0.053	-0.033	-0.005
WBF	1	-0.041	-0.001	0.038	0.001	0.009	-0.024	0.005	0.006	0.006	0.020

3.5.3 Discussion

In general, higher MS, EPS and SNR is believed to indicate a greater climatic influence on tree growth. The autocorrelation model has increased MS, EPS, SNR and decreased SD in nearly all the chronologies (Table 3.9). On average the MS was about 20% higher, EPS was about 5% higher and SNR was 20% higher in residual than in standard chronologies. But there are three exceptions, EPS and SNR are lower in the residual chronologies of sites CRG, RUH and STR.

Table 3.9 Descriptive statistics for the 23 tree-ring chronologies.

Site	Period	Standard chronology					Residual chronology				
		MS	SD	AC1	EPS	SNR	MS	SD	AC1	EPS	SNR
ARM	1446 - 1958	.1602	.2202	.5643	.837	5.135	.1864	.1646	.0052	.859	6.074
CRC	1460 - 1978	.1659	.2885	.6608	.839	5.203	.0000	.1914	-.0267	.858	6.053
CRG	1492 - 1975	.1618	.2518	.7039	.849	5.608	.1924	.1715	.0208	.837	5.139
OKA	1732 - 1976	.1170	.1727	.6473	.799	3.982	.1482	.1290	-.0168	.853	5.817
TRK	1526 - 1978	.1763	.2350	.5761	.823	4.645	.2113	.1858	-.0557	.846	5.474
AHA	1525 - 1992	.1371	.2097	.6535	.865	6.405	.1556	.1396	-.0050	.888	7.914
EMT	1616 - 1990	.1493	.1835	.4795	.898	8.766	.1705	.1501	.0041	.919	11.41
MWO	1464 - 1976	.1158	.1549	.5616	.803	4.087	.1348	.1195	-.0048	.872	6.794
NET	1625 - 1990	.1440	.1858	.5106	.920	11.514	.1689	.1491	-.0131	.940	15.601
TKP	1256 - 1992	.1351	.2530	.7699	.933	13.842	.1758	.1568	-.0257	.939	15.408
UWR	1140 - 1992	.1705	.2466	.6053	.842	5.334	.1900	.1642	-.0045	.906	9.639
CLW	1450 - 1991	.1268	.2230	.7064	.862	6.224	.1641	.1557	-.0459	.896	8.579
FLG	1683 - 1991	.1236	.1848	.6067	.928	12.937	.1564	.1418	.0040	.934	14.080
HIT	1431 - 1991	.1399	.1976	.5830	.842	5.322	.1759	.1567	.0044	.842	5.322
MOA	1490 - 1991	.1269	.2112	.7139	.791	3.790	.1597	.1388	-.0187	.862	6.247
OHT	1585 - 1991	.1481	.2297	.5839	.863	6.277	.1867	.1837	-.0844	.895	8.505
RUC	1473 - 1991	.1230	.2046	.6778	.907	9.791	.1541	.1450	.0104	.921	11.719
RUH	1560 - 1992	.1589	.4198	.7334	.833	4.999	.1958	.1956	.0165	.832	4.949
STR	1626 - 1990	.1454	.2335	.6292	.643	1.801	.1755	.1690	-.0178	.607	1.543
TOA	1511 - 1992	.1301	.1969	.6237	.885	7.704	.1700	.1524	-.0272	.907	9.785
TOB	1332 - 1992	.1425	.2458	.7075	.811	4.286	.1875	.1720	.0052	.846	5.476
TOC	1213 - 1992	.1512	.2623	.6681	.734	2.766	.1865	.1842	-.0523	.775	3.454
WBF	1674 - 1992	.1406	.2336	.6667	.882	7.475	.1742	.1627	-.0414	.906	9.586

3.6 The chronology 'Subsample Signal Strength' (SSS)

The strength of the hypothetical population signal may not always represent the most relevant estimate of changing chronology confidence as a function of decreasing core number. "What confidence can be placed in a n-tree chronology as an estimate of an N-tree chronology?" (n is the number of trees at the early sections of the chronology, N is the maximum number of trees in the chronology, n<N). Using a large number of the possible subgroups of any n trees gives a measure of the scatter about each mean value. This mean value calculated for decreasing n is an experimental realisation of what can be termed as the Subsample Signal Strength (SSS) (Wigley *et al.* 1984). A theoretical expression for the subsample signal strength has been derived by Wigley *et al.* (1984). The expression is

$$SSS = \frac{n(1+(N-1)\bar{r}_{il}}{N(1+(n-1)\bar{r}_{il}} \qquad (3.8)$$

Where n is the number of trees in the subsample chronology

N is the maximum number of trees, and

r_{il} is the mean inter-core correlation coefficient between all possible core pairs except $i = l$.

Equation 3.8 can be expressed in terms of the fractional common variance (â)

$$SSS = \frac{n(\hat{a} + \frac{1-\hat{a}}{N})}{1+(n-1)\hat{a}} \qquad (3.9)$$

Wigley *et al.* (1984) also show that:

$$SSS = \frac{EPS(n)}{EPS(N)} \qquad (3.10)$$

Where: EPS = expressed population signal

N & n are as above

The residual chronology is normally used in dendroclimatic research because the autocorrelation has been removed. The EPS and SSS in table 3.10 was calculated from residual chronologies. Briffa (1984) showed the rise in EPS with tree number declines sharply after about 0.85, so this was also adopted as a reasonable value to use as a threshold. Palmer (1989) also used this 0.85 criteria in his research. In all subsequent work, only the periods where SSS is greater than 0.85 was used.

Table 3.10 Comparison of time periods and the number of trees where EPS and SSS are greater than 0.85

Site	Chronology	EPS > 0.85		SSS > 0.85	
	time-span	Period	N	Period	N
ARM	1446 - 1958	1700 - 1869	11	1591 - 1941	5
CRC	1460 - 1978	1745 - 1978	12	1684 - 1978	6
CRG	1492 - 1975	N. A.	10	1754 - 1975	4
OKA	1732 - 1976	N. A.	10	1797 - 1976	5
TRK	1526 - 1978	1798 - 1978	14	1713 - 1978	7
AHA	1525 - 1992	1717 - 1976	14	1627 - 1976	7
EMT	1616 - 1990	1714 - 1975	9	1697 - 1987	6
MWO	1479 - 1976	1723 - 1976	16	1555 - 1976	8
NET	1625 - 1990	1677 - 1976	9	1670 - 1990	6
TKP	1256 - 1992	1539 - 1976	9	1459 - 1986	6
UWR	1140 - 1992	1433 - 1976	11	1390 - 1992	6
CLW	1450 - 1991	1700 - 1991	11	1616 - 1991	6
FLG	1686 - 1991	1751 - 1991	9	1718 - 1991	6
HIT	1431 - 1991	1497 - 1988	13	1457 - 1991	7
MOA	1490 - 1991	1624 - 1991	14	1556 - 1991	7
OHT	1585 - 1991	1756 - 1991	9	1713 - 1991	5
RUC	1473 - 1991	1611 - 1991	7	1609 - 1991	5
RUH	1560 - 1991	1779 - 1982	16	1660 - 1991	7
STR	1626 - 1990	N.A.	15	1670 - 1990	3
TOA	1511 - 1992	1646 - 1992	10	1597 - 1992	6
TOB	1332 - 1992	1578 - 1992	9	1445 - 1992	4
TOC	1213 - 1992	N. A.	16	1430 - 1990	6
WBF	1674 - 1992	1794 - 1992	8	1733 - 1992	5

Note:

EPS: expressed population signal.
SSS: subsample signal strength.
N: the minimum number of trees needed for EPS > 0.85 or SSS > 0.85.
N.A.: EPS did not exceed 0.85 for any period.

3.7 Chapter conclusions

1. Twelve new sites and 5 updated sites (LaMarche *et al.* 1979a) have been sampled from different places in New Zealand. Another 6 *Libocedrus bidwillii* chronologies that were not updated were also discussed in this chapter.

2. About 80% of the cores taken were able to be cross-dated. The remeasurement of selected cores showed that the measurements were highly acceptable (more than 86% accepted at 1% level and all others accepted at 5% level).

3. The quality of cross-dating was verified using the COFECHA program. Based on the suggestion of COFECHA, some measured data series were rejected. All the cores included in the final chronologies were highly correlated with each other.

4. No obvious growth trend was seen in most of the *Libocedrus bidwillii* ring-width data series, but its appearance in some cores led to the use of double detrending methods for standardisation. Double detrending also increased the SNR compared with single detrending (using only a spline).

5. The robust mean chronology computation method can decrease error variance compared with arithmetic mean chronology computation.

6. The chronologies developed from different double detrending methods showed that there are very similar signals at high frequency bands but very different signals at the low frequency bands. Only ERH+SP67% methods kept the signals which were longer than 120 years. There were very high correlations among the chronologies using the different methods.

7. The chronology developed by ERH+SP40 double detrending method had the highest EPS and SNR. Using longer spline filters, such as ERH+SP67% double detrending, resulted in MS increasing 1.68%, EPS and SNR decreasing 2.9% and 22.3% respectively.

8. The results from the spectral analysis of climate data showed that all the temperature series had similar cycles and included some low frequency peaks. The rainfall series are very different from different places but all of them included some low frequency signals. In order to keep more climate information in the chronology, ERH+SP67% method was selected as the final standardisation method although this lead to some reduction of EPS and SNR.

9. All the chronologies contained significant autocorrelation which was removed by the ARSTAN program with AIC model selection. No significant autocorrelations were left in the residual chronologies produced by this method. Autocorrelation removal also improved EPS and SNR of the chronologies.

10. A sub-sample signal strength (SSS) of 0.85 was chosen to delimit the useable chronology period for later climate modelling.

CHAPTER FOUR
CHRONOLOGY COMPARISON

4.1 Introduction

The aim of this chapter was to explore the relationships between the different site chronologies (derived in the previous chapter; Chapter 3). The main questions asked were:

- What was the effect of separation distance between the site chronologies ?
- Was there an influence of latitude, longitude and altitude between the chronologies ?

The first question relates to the spatial extent or strength of the chronology patterns while the second investigates the level of influence from broad scale environmental parameters. The most commonly investigated environmental factor is altitude and its influence on chronology signals (e.g. Norton, 1983a). Both latitude and longitude were also investigated because of the complex topography in New Zealand and the strong influence on the climate. The sites were more closely investigated using spectral analysis. Such investigations are important for the optimal selection of sites for subsequent climate modelling.

In order to determine if there was some interactive effects between the different environmental parameters, or some other important but unknown influence, all 23 chronologies were pooled together and investigated using principal component analysis (PCA).

Finally the effect of the age of the trees used in the chronologies was also investigated. One of the fundamental assumptions of dendrochronology is the "uniformitarianism principle" (Fritts, 1976). The question being asked was:

- Does the strength of the signal in common between sites vary because of the age of the trees ?

In such mesic environments where competition plays a significant role then some variation through time is possible and trees may become more or less climatically "sensitive" during their life-span.

4.2 Methods

The inter-chronology comparison was made on the correlation matrix for all 23 chronologies. The common period 1734 to 1958 was used in this analysis. The correlation coefficients between 4 sites and all the other sites were shown in separate detailed site maps (Figure 4.1) as a demonstration of spatial relationships.

Following the approach used to analyse a group of European oak chronologies (Briffa, 1984), the relationships between separation distance and the correlation coefficients were analysed using simple regression techniques (4.3.2). The same approach was done for altitudinal gradients (4.3.4). Spectral analysis was used to find any similarity and dissimilarity cycles among sites from different places. Coherency analysis (co-spectral analysis between several time-series using the Fast Fourier Transform) was used to further investigate the frequency-dependent relationships among the sites (Guiot, 1995). Nine chronologies were used in the spectral analysis in order to more fully characterise their frequency-dependent properties. Three sites from the same mountain (TOA, TOB, TOC) representing an altitudinal gradient, three sites (UWR, HIT, NET) from a similar latitude but a different longitudes and another three sites (TKP, MOA, RUH) representing latitude differences were selected.

Principal components analysis (PCA) over the period 1734 to 1958 was used to further identify any groups in the 23 chronologies. Only the first 3 principal components (PCA) were shown in the figures. An explanation for the observed associations was then attempted/given.

In order to examine the effects of tree age on the chronology, DBH (Diameter at Breast Height) was used as a criteria for selection. This was because the true age of the tree was not known for most of the sites (due to sampling not reaching the centre of the tree or the tree being rotten in the centre). Stewart and Rose (1989) reported that the relationship between age and diameter of living *Libocedrus bidwillii* was significant on gley podzol and compound yellow-brown earth soils (refer to Chapter 1). The relationship between age and diameter in sites TOA, TOB and TOC can be described as: y(DBH)=0.0519 * (age) + 36.0 ($F=80.72$, $p=0.0001$). Trees 50cm DBH were 270 years old and 80cm DBH trees were about 850 years old on these three sites (TOA, TOB & TOC). These results suggested that the diameter could be used as an indicator of age for *Libocedrus bidwillii.* The comparison was made between the chronologies developed from "small" trees (DBH < 50cm), "middle" trees (50cm ≤ DBH < 80cm), "big" trees (DBH ≥ 80cm) and all trees combined. Three sites (TOA, TOB, TOC) were discussed in detail.

4.3 Results

4.3.1 Inter-chronology correlation

The cross correlations (Table 4.1) generally show a highly significance between the chronologies. Most of the chronology correlations are significant at the 1% level. One site (TRK), however, was noticeably different with 9 in 22 cross-correlations being non-significant at the 1% level. Two other South Island sites (AHA and CRC) also did not significantly correlate with other sites.

Figure 4.1A-B show the interchronology correlations for four example sites. Two sites were selected from the North Island and 2 from the South Island to broadly represent latitude and longitude differences. All the sites on the West Coast of the South Island had low correlations with three out of the four example sites (the exception was the North Island west coast site - NET). All the sites from the North Island had relatively high correlations with the four example sites.

Table 4.1 Cross-correlations between the different chronologies for the common time interval 1734-1958.

Site	ARM	CRC	CRG	MWO	OKA	TRK	AHA	EMT	NET	TKP	UWR	CLW	FLG	HIT	MOA	OHT	RUC	RUH	STR	TOA	TOB	TOC	WBF
ARM	1.0																						
CRO	.141	1.0																					
CRG	.535	.190	1.0																				
MWO	.305	.334	.264	1.0																			
OKA	.353	.218	.519	.255	1.0																		
TRK	.070	.765	.133	.276	.148	1.0																	
AHA	.084	.237	.204	.246	.316	.168	1.0																
EMT	.425	.163	.450	.361	.375	.098	.249	1.0															
NET	.438	.287	.481	.361	.384	.248	.230	.739	1.0														
TKP	.459	.381	.332	.553	.281	.277	.216	.437	.467	1.0													
UWR	.401	.012	.360	.285	.322	-.052	.260	.572	.497	.347	1.0												
CLW	.449	.345	.361	.560	.237	.227	.209	.443	.422	.669	.445	1.0											
FLG	.373	.444	.301	.444	.369	.288	.403	.506	.469	.470	.353	.574	1.0										
HIT	.486	.300	.477	.580	.349	.175	.224	.577	.557	.729	.495	.683	.522	1.0									
MOA	.461	.107	.427	.294	.363	.038	.348	.483	.463	.420	.450	.429	.430	.442	1.0								
OHT	.383	.318	.323	.615	.286	.263	.179	.400	.447	.573	.339	.819	.566	.622	.403	1.0							
RUC	.446	.335	.375	.653	.295	.223	.236	.512	.495	.648	.414	.856	.605	.738	.443	.827	1.0						
RUH	.303	.463	.312	.421	.407	.336	.680	.323	.321	.388	.261	.399	.570	.384	.503	.371	.396	1.0					
STR	.369	.246	.387	.415	.248	.126	.206	.707	.652	.516	.432	.515	.476	.545	.391	.469	.531	.332	1.0				
TOA	.429	.368	.425	.549	.303	.288	.271	.466	.487	.556	.305	.687	.602	.616	.474	.670	.716	.536	.436	1.0			
TOB	.467	.411	.427	.559	.305	.295	.220	.536	.606	.677	.390	.737	.582	.750	.453	.674	.742	.425	.529	.797	1.0		
TOC	.470	.367	.463	.576	.377	.243	.260	.622	.646	.688	.445	.668	.622	.760	.482	.604	.710	.470	.585	.713	.806	1.0	
WBF	.225	.384	.261	.286	.255	.295	.096	.291	.326	.275	.155	.292	.414	.336	.109	.279	.330	.237	.215	.356	.319	.299	1.0
Sig.*	3	4	1	0	1	9	4	2	0	0	3	0	0	1	3	1	0	0	1	0	0	0	3

* Number of cross-correlations not significant at 1% level for each site. The critical value for the 5% significance level is 0.138 and the 1% level is 0.181.

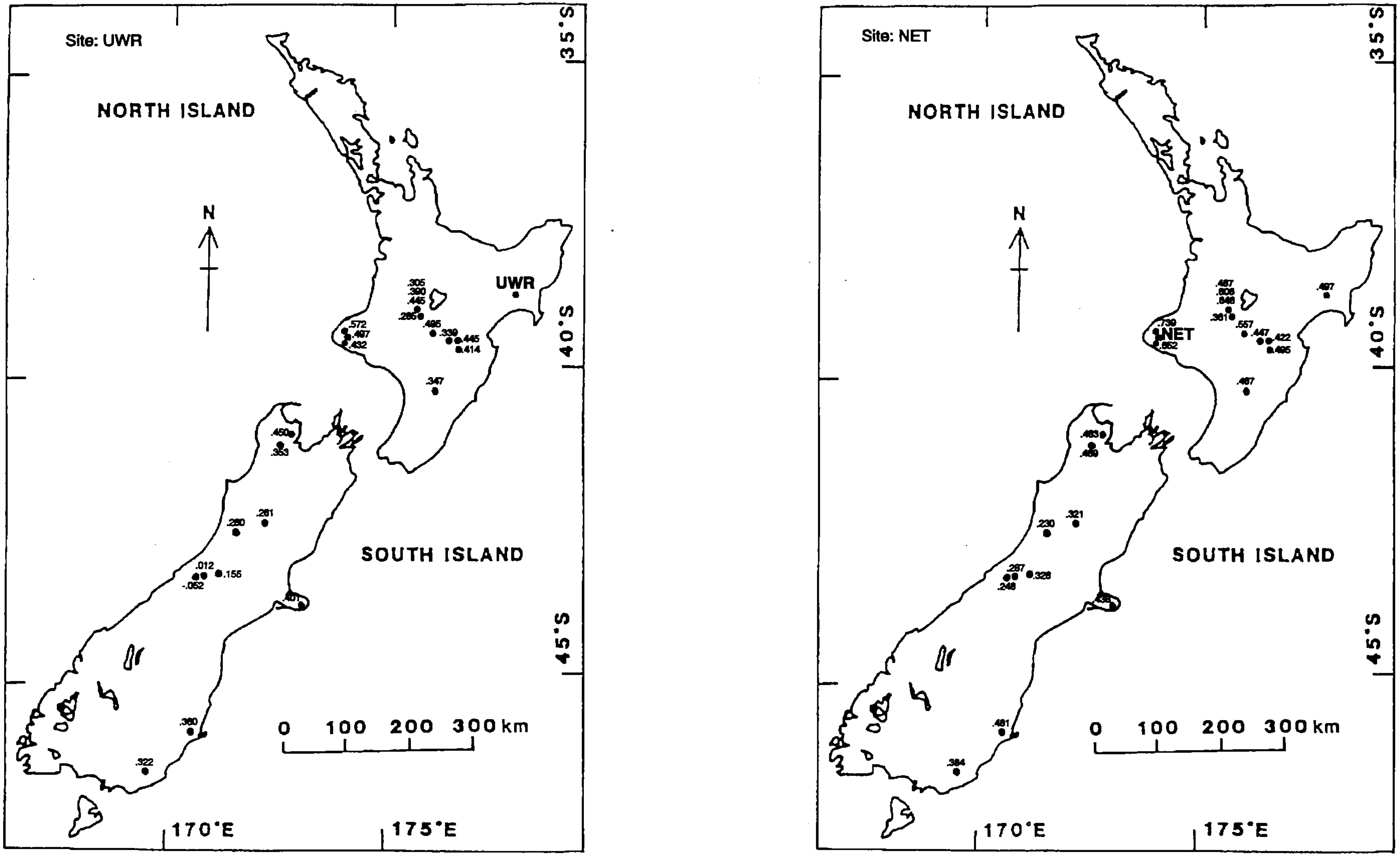


Figure 4.1A Interchronology correlations for selected chronologies (sites UWR and NET).

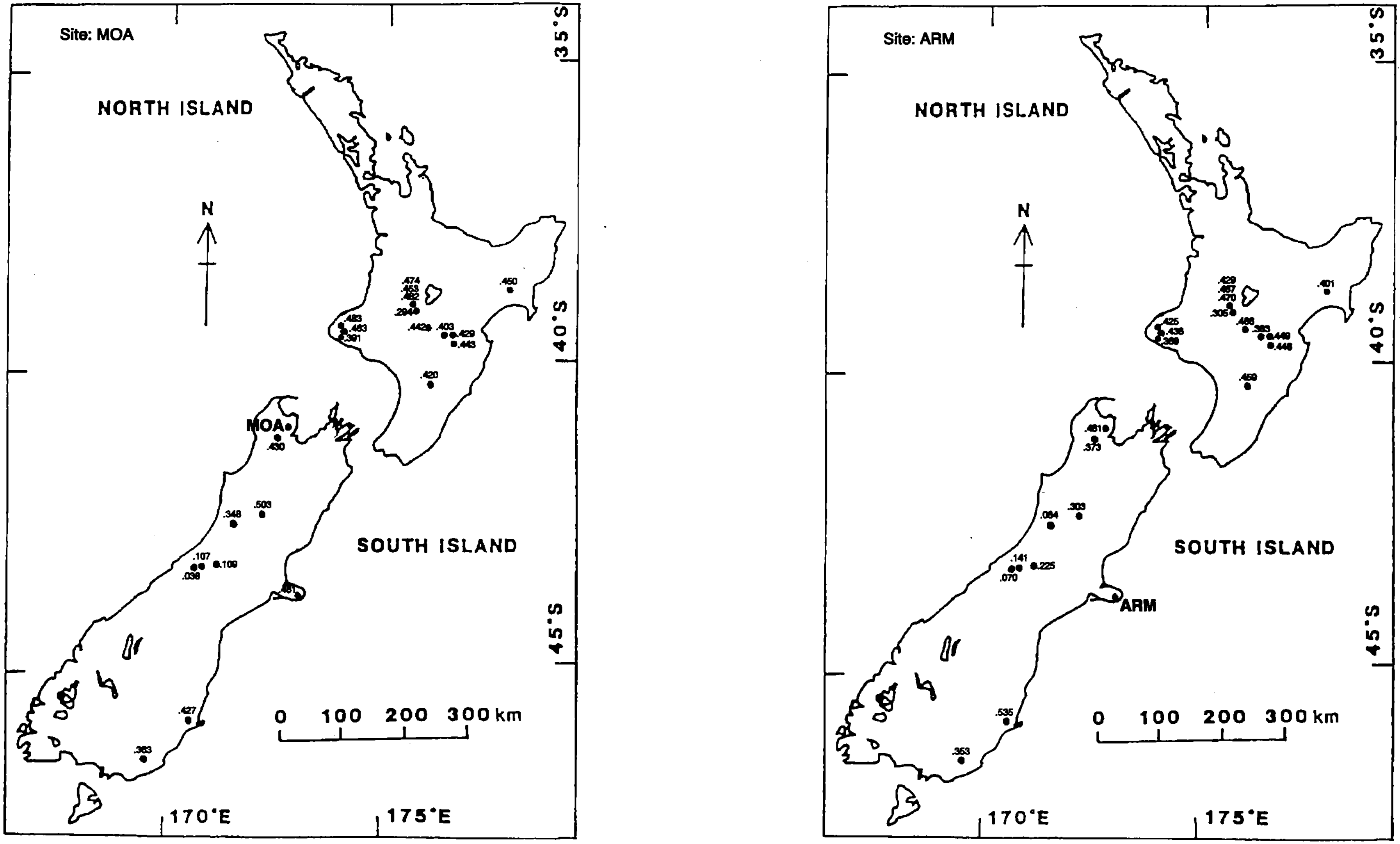


Figure 4.1B Interchronology correlations for selected chronologies (sites MOA and ARM).

4.3.2 Chronology correlation and separation distance

The fitted linear relationship for all points had an F value of 94.85 and was statistically significant at the 0.001 level (Table 4.2). By calculating linear regressions in successive steps, with points separated by progressively greater distances being included at each step (Table 4.2), it was shown that the fall in correlation with separation distance increases (as measured by B, the slope of the line becomes less negative). Consequently, some transformation of the distance was suggested by these results. A simple $\log_{10}$ transformation was used and the resulting F value for the regression between chronologies and the log of the separation distance for all points rose to 133.55. Repeating the regressions for the same steps as shown in Table 4.2, the slope of the line was seen to be more stable, indicating that the transformation was a reasonable one.

Table 4.2 Summary of simple regressions of correlation coefficients between chronologies and their separation distance[1]

	F[2]	A[3]	B[4]	N[5]
correlation coefficient vs separation distance				
All pairs (up to 1100km)	94.85***	.534	-.000035	253
Pairs separated by <300 km	66.62***	.658	-.00122	123
Pairs separated by <400 km	57.11***	.623	-.000864	146
Pairs separated by <500 km	86.70***	.599	-.000669	177
Pairs separated by <600 km	111.52***	.578	-.000530	218
Pairs separated by <700 km	113.74***	.573	-.000507	224
correlation vs log transformed separation distance				
All pairs (up to 1100km)	133.55***	.875	-.196	250
Pairs separated by <300 km	39.89***	.873	-.194	120
Pairs separated by <400 km	45.30***	.863	-.188	143
Pairs separated by <500 km	76.76***	.890	-.203	174
Pairs separated by <600 km	112.09***	.894	-.205	215
Pairs separated by <700 km	117.81***	.893	-.205	221

Note:

1 For the period 1734 to 1958 against their separation distance in kilometre or log transformation;
2 F-value with a '*' is significant at 0.05 level, with '**' is significant at 0.01 level and '***' is significant at 0.001 level;
3 A is the regression constant;
4 B is the slope;
5 N is the number of pairs included in the regression.

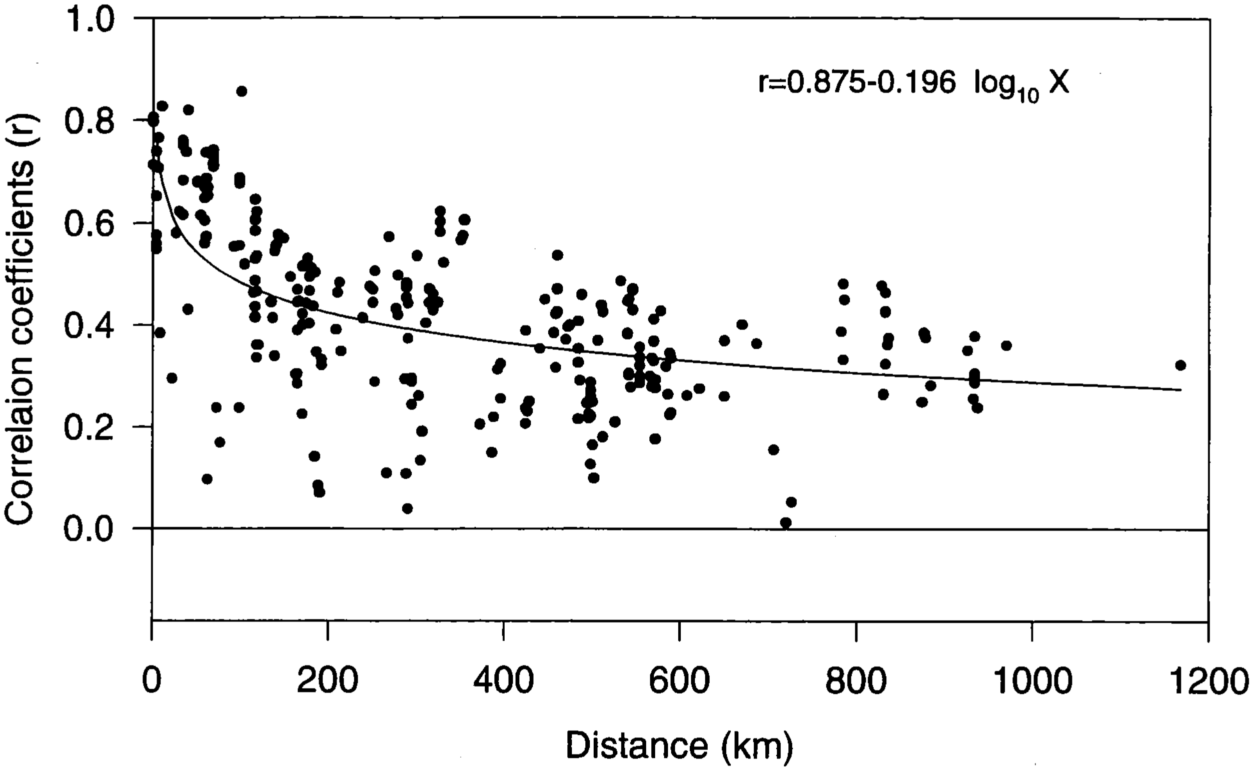


Figure 4.2 Correlation coefficient between chronologies plotted against their separation distance. The solid line was the fitted regression line.

The overall regression is given by:

$$r = 0.875 - 0.196 \log_{10} X$$

where X is the separation distance, and r is the correlation coefficient.

Figure 4.2 shows the correlation coefficients plotted against the separation distance between the sites.

4.3.3 Spectral analysis

The spectral density of sites UWR, HIT and NET (Figure 4.3A-C) showed there was less low frequency variance in site UWR than in sites HIT and NET. There was more high frequency variance (from 2 to 10 years) in site UWR. The coherence analysis (Figure 4.3D-F) showed the cycles among the three sites were different. Comparing with other pairs (UWR-HIT & UWR-NET), HIT and NET were similar in their periodic cycles.

The spectral density of TKP, MOA and RUH (Figure 4.4A-C) showed that there were less low frequency peaks in site MOA than in sites TKP and RUH. The coherence analysis of these three sites (Figure 4.4D-F) showed that there were differences among these three sites.

4.3.4 The influence of altitude

This was carried out in a similar manner to the previous study of the effect of separation distance (section 4.3.2). The inter-chronology correlations compared with altitude were investigated by looking at the significance of the regression (Table 4.3). The sharp decline in the slope of the line as pairs of sites are introduced with a difference of less than 300 m suggests some transformation may be necessary. However the log transformation was found not to improve the value so was not used.

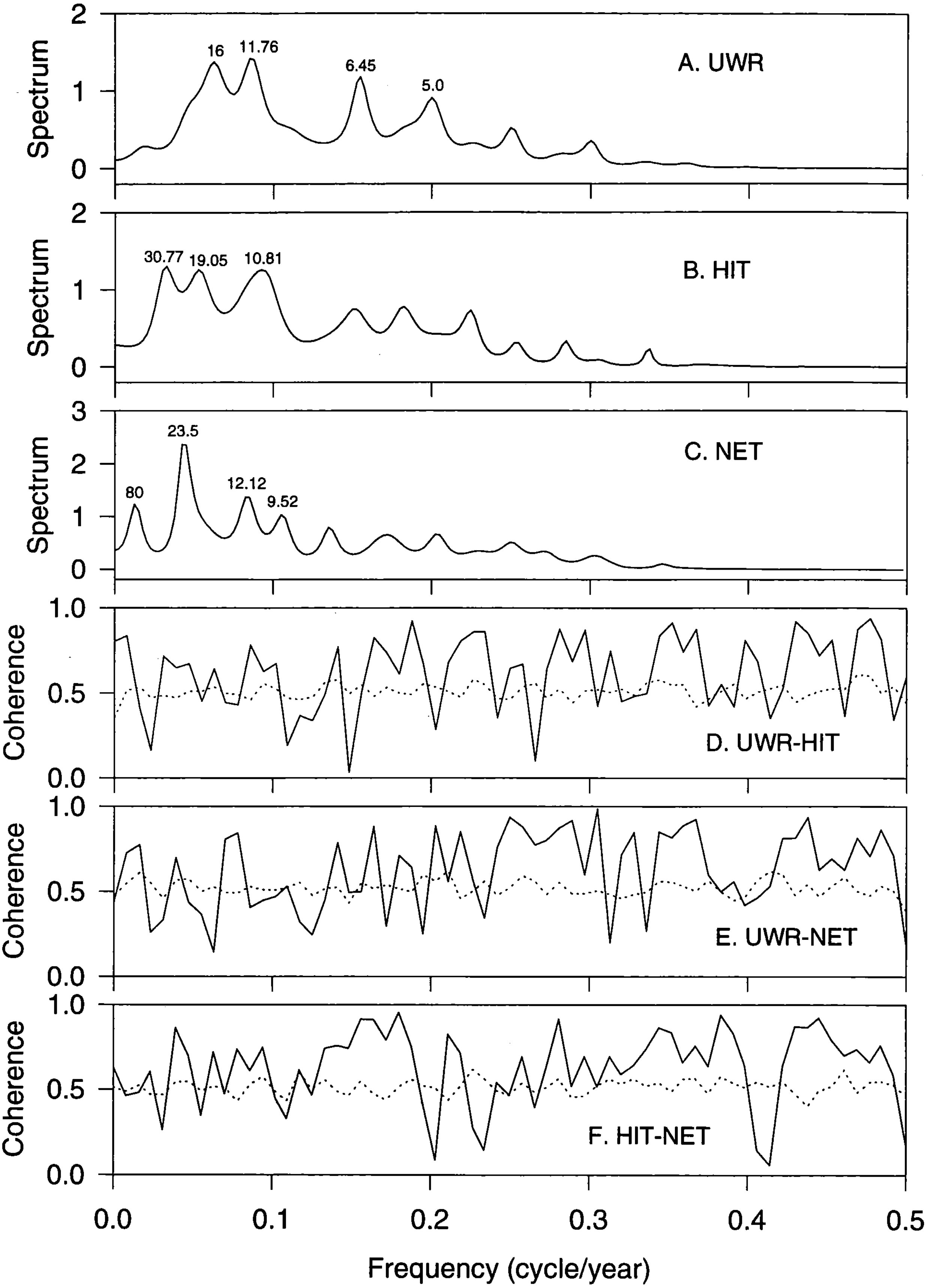


Figure 4.3 Spectral density (A-C) and coherence (D-F) of different longitude sites. Analysis period 1629-1990. ——— Spectral density or coherence. ········ 95% confidence bands.

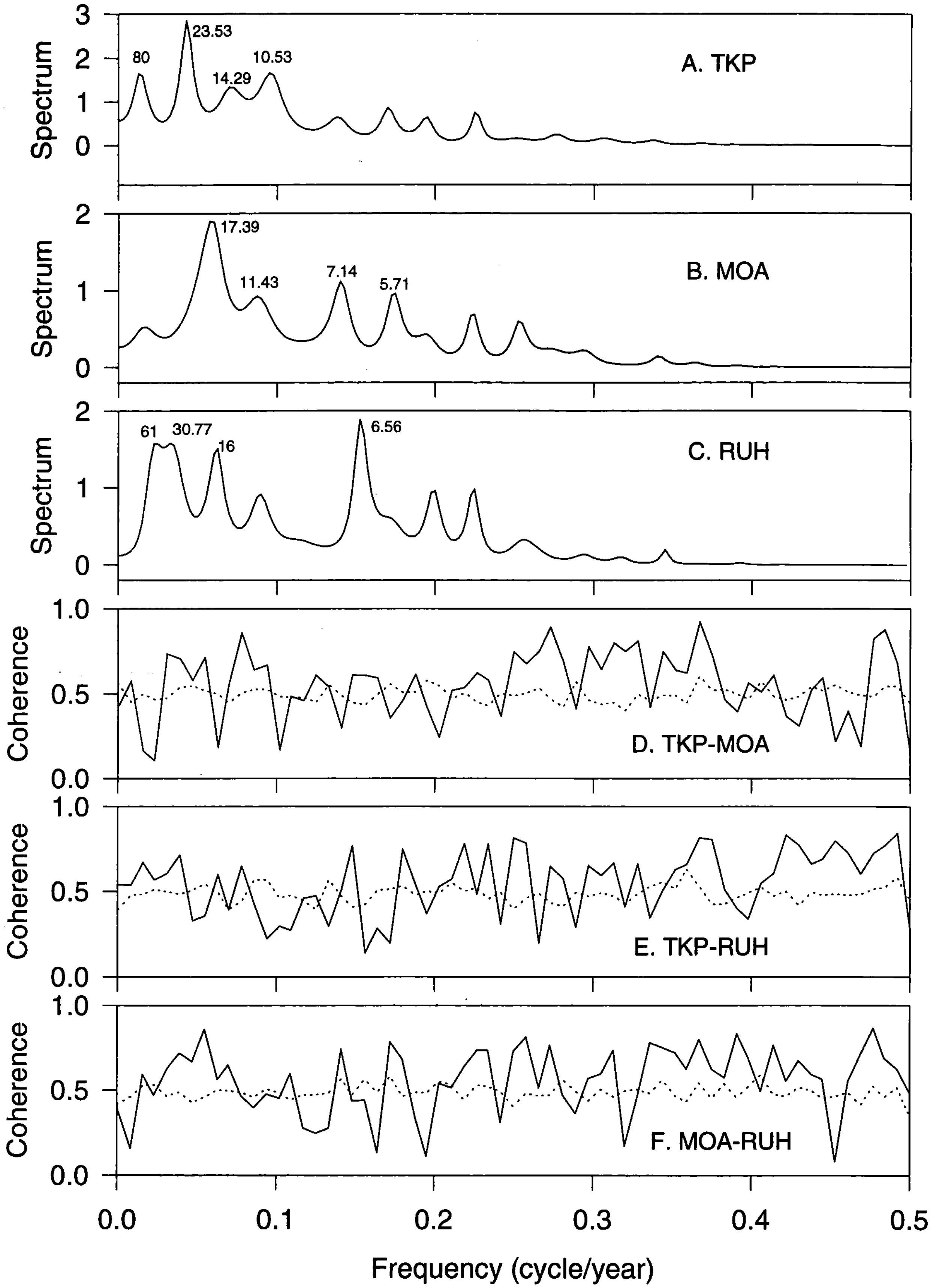


Figure 4.4 Spectral density (A-C) and coherence (D-F) of different latitude sites. Analysis period 1563-1991. ——— Spectral density or coherence. ········ 95% confidence bands.

Table 4.3 Summary of simple regressions of correlation coefficients between chronologies and their altitude difference[1]

	F[2]	A[3]	B[4]	N[5]
correlation vs altitude difference				
All pairs (up to 1000m)	36.82***	.488	-.000265	253
Pairs < 100m	5.69*	.566	-.00252	56
Pairs < 300m	2.07	.485	-.000258	161
Pairs < 500m	5.90*	.481	-.000217	212
correlation vs log of altitude difference				
All pairs (up to 1000m)	25.36***	.682	-.118	252
Pairs < 100m	3.90	.749	-.191	55
Pairs < 300m	1.70	.557	-.0533	160
Pairs < 500m	4.91*	.582	-.0669	211

Note:
1 between two chronologies over the period 1734 to 1958, against the altitude difference and log of altitude difference;
2 F-value with a '*' is significant at 0.05 level, with '**' is significant at 0.01 level and '***' is significant at 0.001 level;
3 A is the regression constant;
4 B is the slope and N is the number of pairs included in the regression.

The best fitted linear relationship had a F-value of 36.82 (statistically significant at the 0.001 level).

The overall regression was given by :

$$r = 0.488 - 0.000265 X$$

where X was the difference in altitude. r was the correlation coefficient.

Figure 4.5 shows the correlation coefficients plotted against the differences in altitude between the sites.

Sites TOA, TOB and TOC were selected to do spectral and coherence analysis (Figure 4.6). The biggest difference among the three spectral densities was about 10 years (0.1 cycle per year). There was a high peak around 9 years in site TOA but a 12 year peak in the other two sites. Strong high frequency periodicity was absent

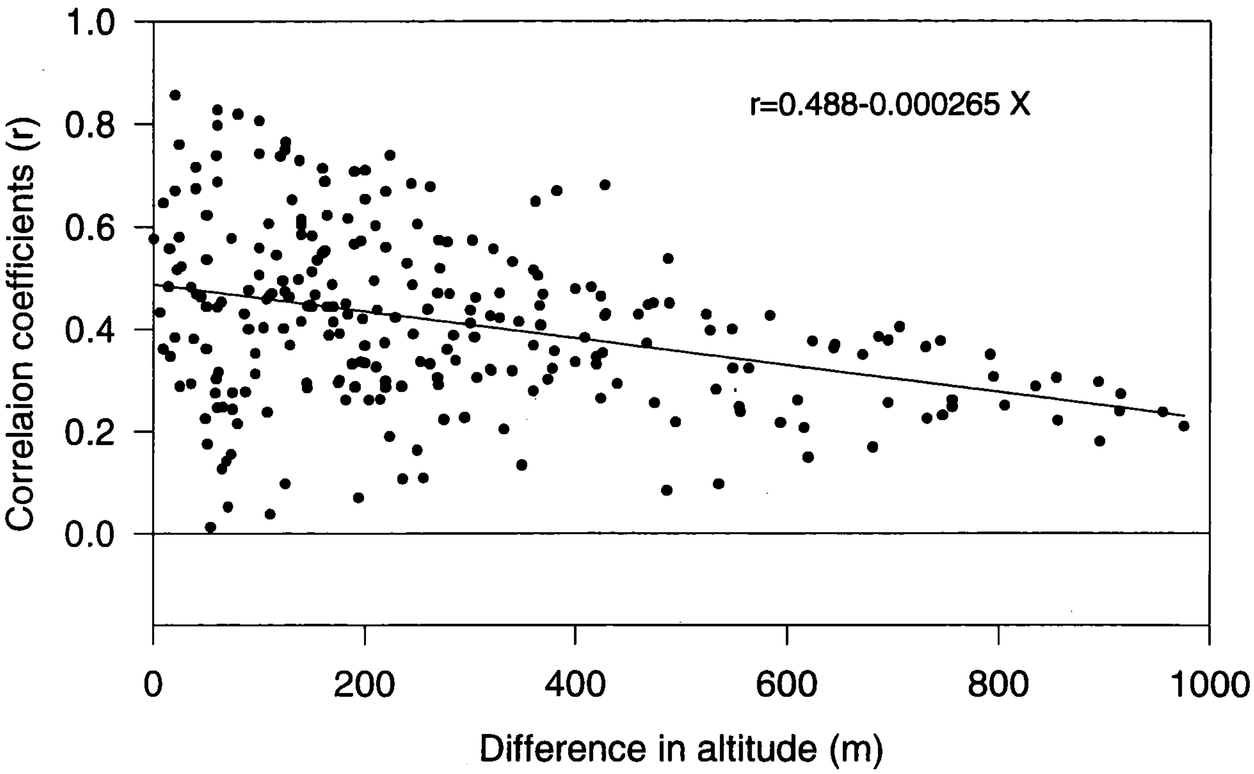


Figure 4.5 Correlation coefficient between chronologies plotted against their altitude difference. The solid line was the fitted regression line.

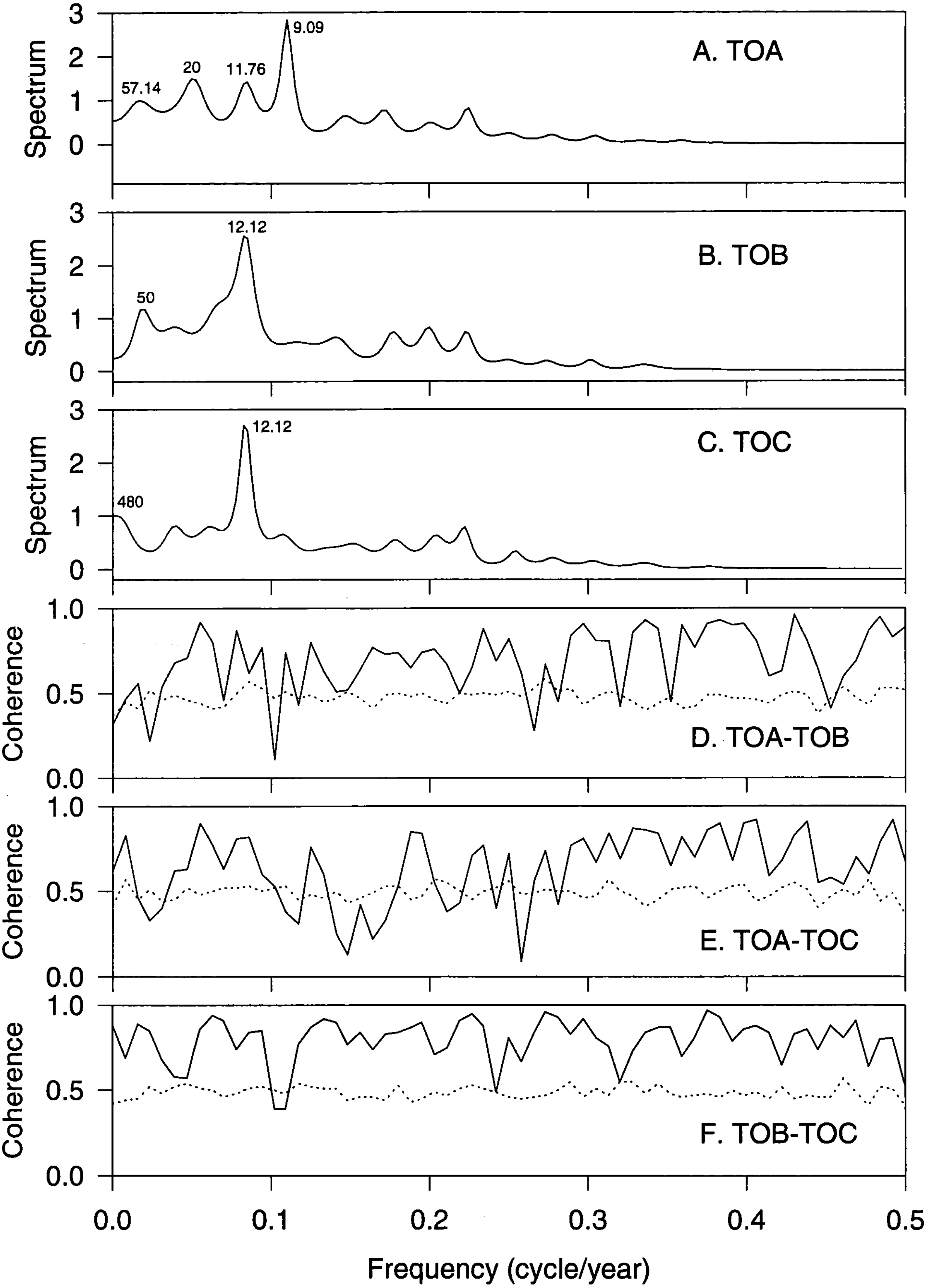


Figure 4.6 Spectral density (A-C) and coherence (D-F) of different altitude sites (TOA, TOB & TOC). Analysis period 1513-1992. ——— Spectral density or coherence. ········ 95% confidence bands.

from these three sites. Coherence analysis of these three sites was shown in Figure 4.6D-F.

4.3.5 PCA analysis of chronologies

Principal components analysis (PCA) over the period 1734 to 1958 was used to further examine the geographical pattern of the 23 chronologies. In the PCA analysis of the residual chronologies, 85.2% of the total variance was explained by the first ten components. The first three, explaining 62.0% in total, accounted for 45.9%, 8.8%, and 7.3% of the total variance respectively. The spatial patterns (i.e. component loadings or weights) were shown in Figure 4.7. According to the loadings on the first three components, the sites can be grouped into four groups. Because of the much higher variance explained by the first PC, the group process was more based on the pattern of PC1-PC2 and PC1-PC3. There were 8 sites in Group A, 5 sites in B, 5 sites in C and 4 sites in D. Only site OKA was not included in any group.

4.3.6 Comparisons of chronologies developed from "big" and "small" trees

Table 4.4 The statistics of chronologies developed from different tree sizes

Site	Period	Trees / cores	Mean Width	MS	SD	AC1	EPS	SNR
TOA (all trees)	1511-1992	25/43	.60	.170	.152	-.027	.907	9.785
TOA (DBH < 50 cm)	1580-1992	10/19	.55	.174	.156	-.061	.837	5.126
TOA (DBH ≥ 50 cm)	1511-1992	14/23	.68	.181	.163	-.040	.871	6.776
TOB (all trees)	1332-1992	15/27	.50	.188	.172	.005	.846	5.476
TOB (DBH < 80 cm)	1350-1992	8/13	.53	.200	.180	.001	.739	2.828
TOB (DBH ≥ 80 cm)	1332-1992	6/10	.48	.211	.194	.019	.705	2.389
TOC (all trees)	1213-1992	14/24	.56	.187	.184	-.052	.775	3.454
TOC (DBH < 80 cm)	1213-1992	6/12	.59	.187	.175	.000	.618	1.616
TOC (DBH ≥ 80 cm)	1268-1992	7/10	.55	.183	.171	.000	.651	1.866

The descriptive statistics of chronologies developed from different tree sizes was shown in Table 4.4. Sites TOA, TOB and TOC were from the same mountain (Mt. Hauhungatahi). Table 4.5 gives the cross-correlations between chronologies

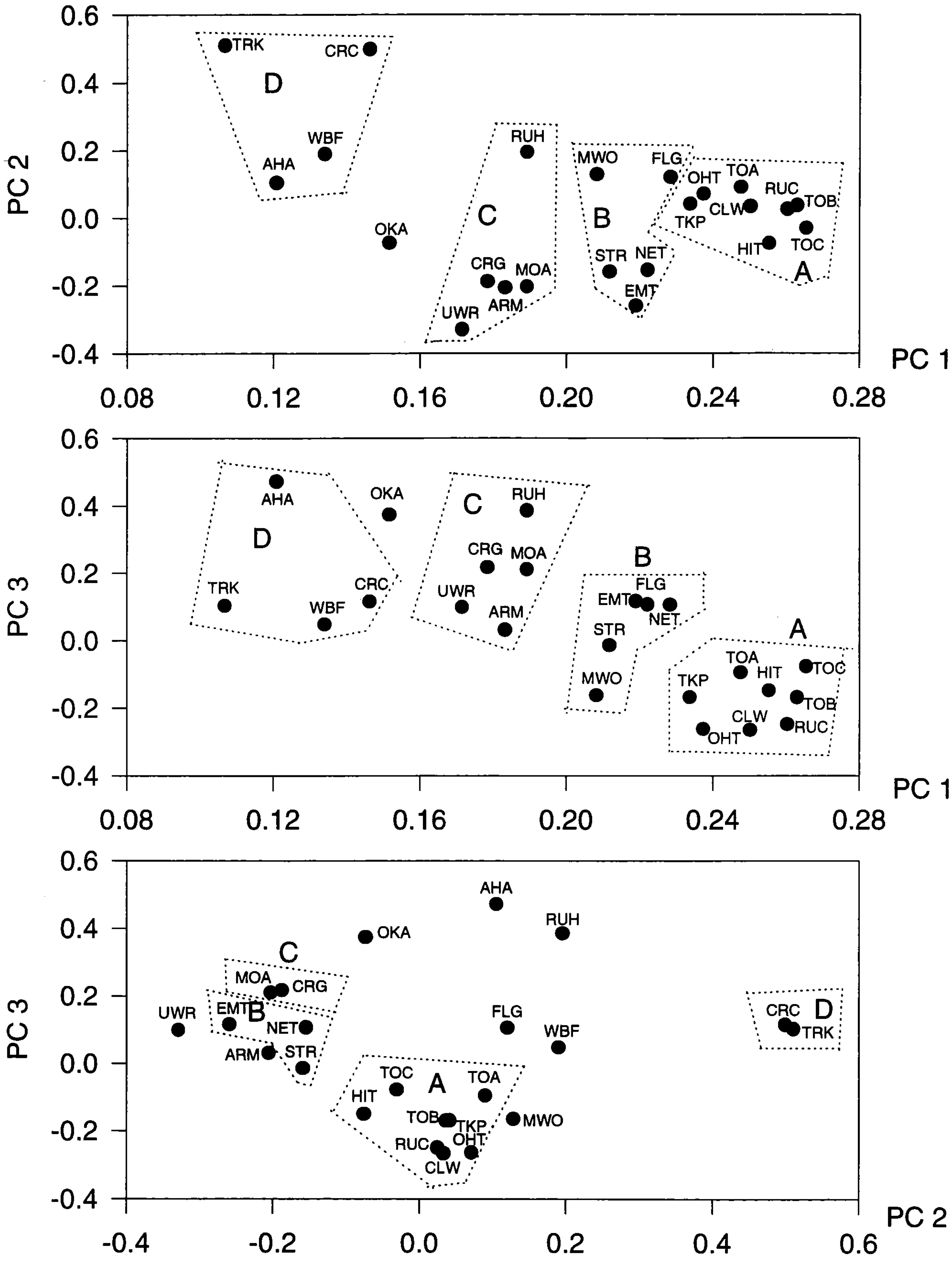


Figure 4.7 The loadings pattern for the first three components of PCA analysis for the 23 chronologies. PC1 explained 45.9%, PC2 explained 8.8% and PC3 explained 7.3%.

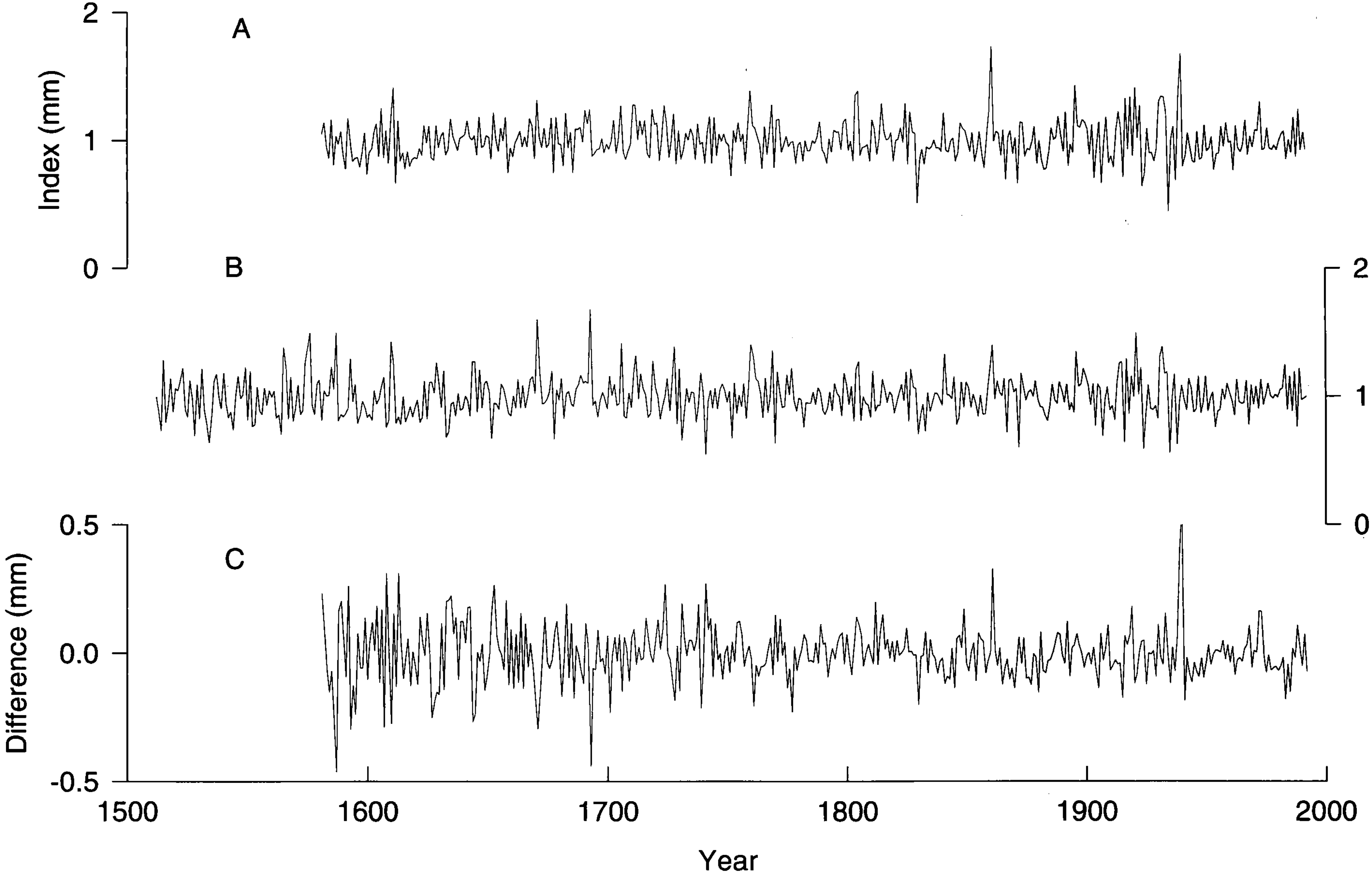


Figure 4.8 Comparison of chronologies for 'old' and 'young' trees from site TOA. A. Chronology developed from DBH < 50cm trees. B. Chronology developed from DBH ≥ 50cm trees. C. The difference between A and B.

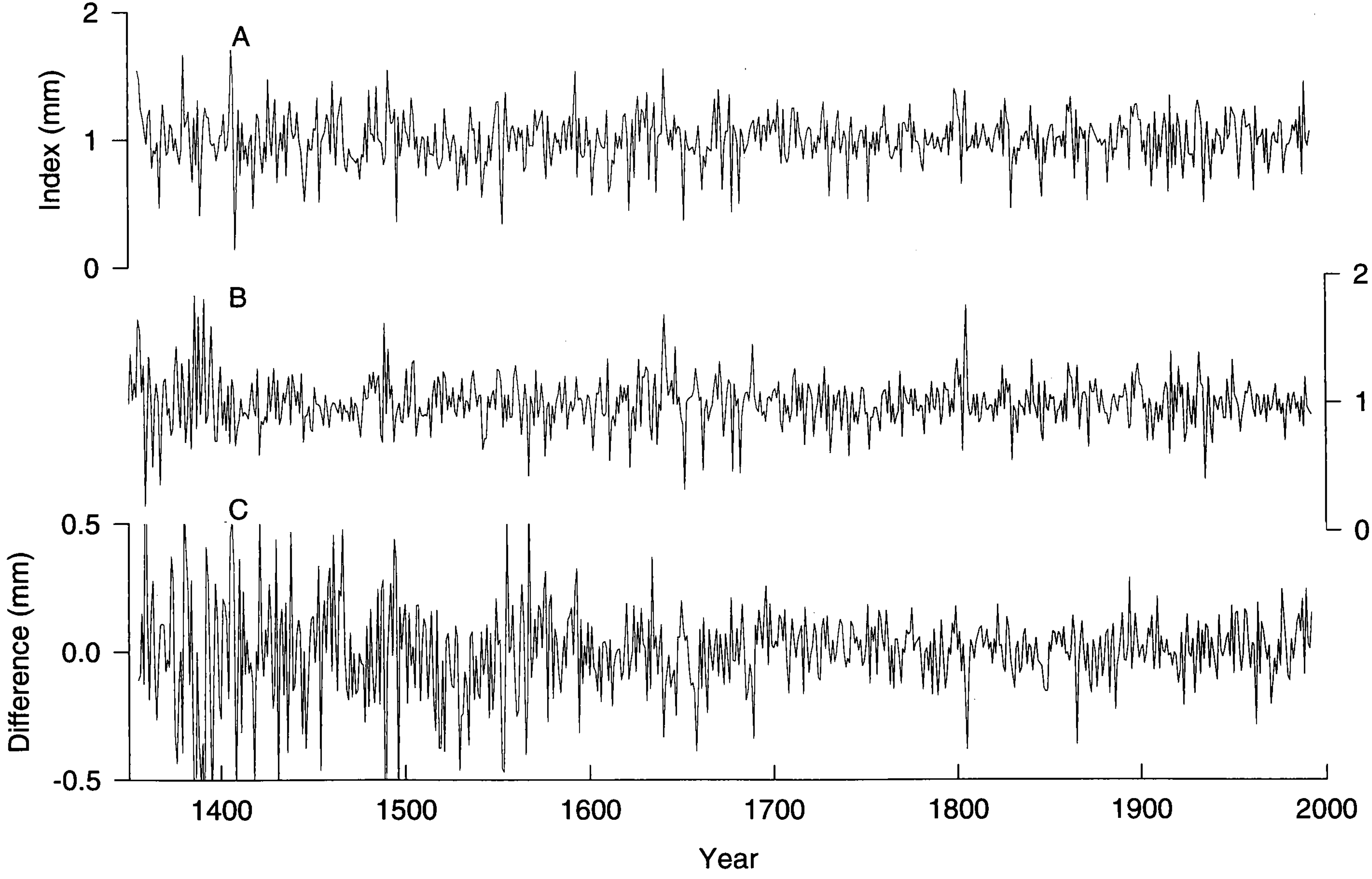


Figure 4.9 Comparison of chronologies for 'old' and 'young' trees from site TOB. A. Chronology developed from DBH < 80cm trees. B. Chronology developed from DBH ≥ 80cm trees. C. The difference between A and B.

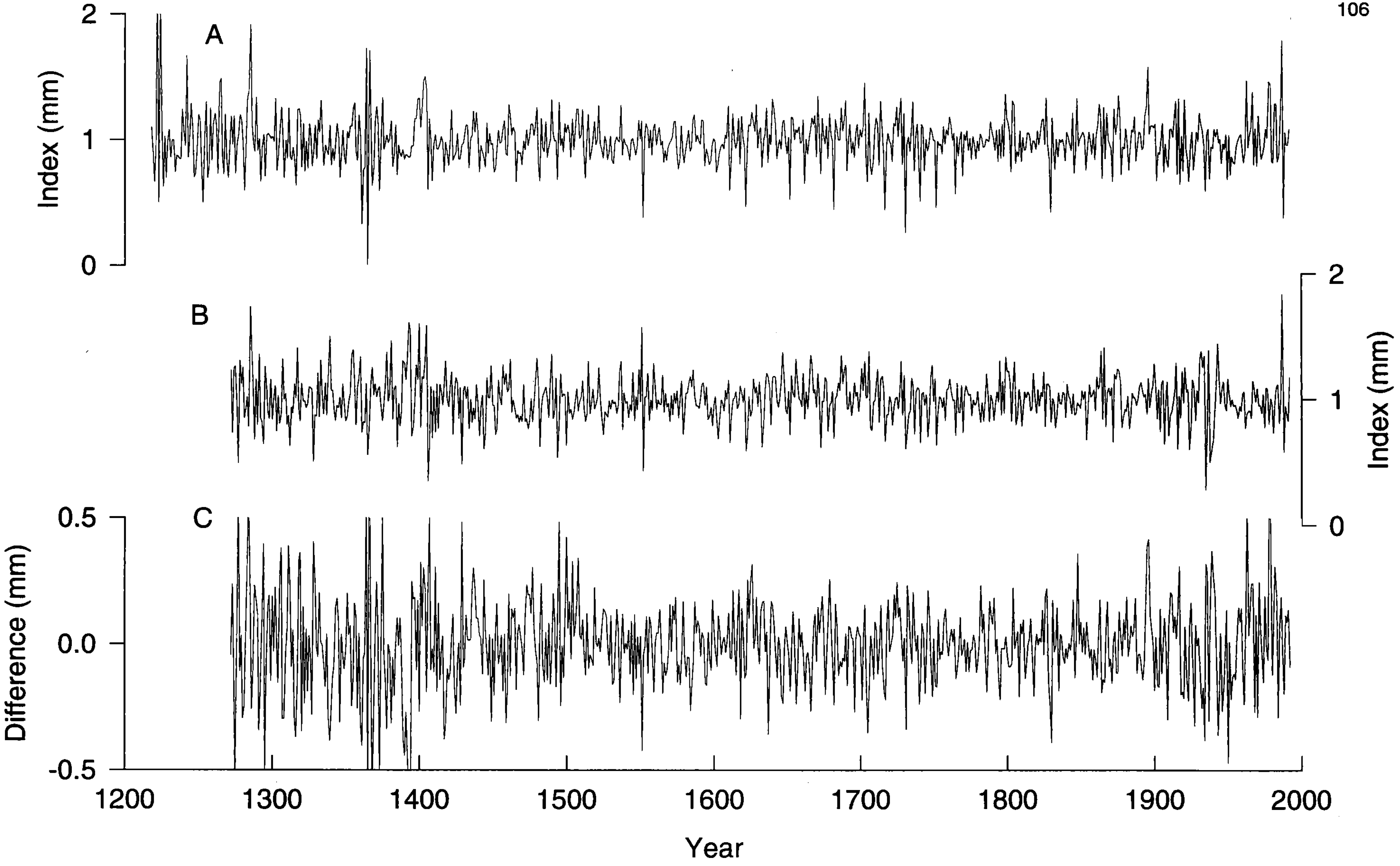


Figure 4.10 Comparison of chronologies for 'old' and 'young' trees from site TOC. A. Chronology developed from DBH < 80cm trees. B. Chronology developed from DBH ≥ 80cm trees. C. The difference between A and B.

developed from different tree sizes. Figures 4.8-10 compare the results for the 'big' and 'small' trees. In all three figures, the upper figure shows the chronologies developed from small trees; the middle figure shows chronologies developed from big trees; the bottom diagram shows the difference between the index values of the 'old' and 'young' chronologies. Positive values indicate the chronology for small trees has a larger index value than the chronology for the big trees.

Table 4.5 The correlation coefficients of chronologies developed from different size trees[1]

Chronology	TOA	TOA1	TOA2	TOB	TOB1	TOB2	TOC	TOC1	TOC2
TOA (all trees)	1.00								
TOA1 (DBH < 50cm)	.920	1.00							
TOA2 (DBH ≥ 50cm)	.927	.744	1.00						
TOB (all trees)	.707	.598	.710	1.00					
TOB1 (DBH < 80cm)	.650	.539	.662	.936	1.00				
TOB2 (DBH ≥ 80cm)	.659	.547	.669	.931	.811	1.00			
TOC (all trees)	.606	.512	.621	.765	.731	.704	1.00		
TOC1 (DBH < 80cm)	.541	.469	.549	.678	.651	.605	.904	1.00	
TOC2 (DBH ≥ 80cm)	.548	.446	.565	.655	.624	.634	.866	.642	1.00

Note: 1 Analysis period 1580-1992, all significant at 0.01% level.

The number of different sized trees in all available chronologies was shown in Table 4.6. There were 8 sites which had nil or only 1 tree larger than 80cm in DBH. These chronologies can be looked at as relatively young sites. There were four sites with few trees below 50cm in DBH (less than 10%), these were relatively old sites. Only a small number of sites included a range of tree sizes.

Table 4.6 Number of trees/cores of different diameter classes in the chronologies[1]

Site	Total	DBH < 50cm	50cm ≤ DBH < 80cm	DBH ≥ 80cm
AHA[2,3]	15/26	9/13	5/11	0
TKP[2]	11/17	7/13	4/4	0
UWR[2]	14/29	1/2	7/15	6/12
CLW	18/45	3/7	10/20	5/17
FLG	20/33	8/13	11/19	1/1
HIT[3]	49/52	3/3	16/16	29/31
MOA	20/49	15/34	5/15	0
OHT	17/40	4/8	12/30	1/2
RUC	29/73	4/8	14/34	11/31
RUH	18/40	10/23	7/14	1/3
TOA[3]	25/43	10/19	14/23	0
TOB[3]	15/27	0	8/13	6/10
TOC[3]	14/24	0	6/12	7/10
WBF	15/31	1/1	14/30	0

Note: 1 diameter was not measured in some sites, like EMT, NET, STR.
2 only included the updated data.
3 some trees had no record of their diameter.

4.4 Discussion

The correlation analysis of all the 23 *Libocedrus bidwillii* sites shows that there was a significant relationship between correlation coefficients and distance apart. The strength of the correlations decline with increasing separation distance. However, this relationship is not entirely explained by the regression line, since at about 200-400 km, 700 km and 800-900 km, the correlation coefficients obviously do not fit the curve. Examination of the correlation matrix shows these points to be associated with combinations of intercorrelations between sites CRC, TRK and other sites less than 500 km distant (as mentioned above these two sites have very low correlations with other sites). At 800-900 km distance, the correlation between site CRG and some North Island sites are very high. The high correlations from such widely separated sites implies a macro-climatic influence. Ahmed & Ogden (1985) reported that the regression curve of the correlation coefficient between each cross-matched kauri (*Agathis australis*) chronology pair on their distance apart was not significant

(Y=0.467-0.000263X; where Y is correlation coefficient, X is distance between sites which is up to 350km, r=0.224, n=55, N.S.). Norton (1983a) showed that the regression of the correlation between each Craigieburn Range timberline *Nothofagus solandri* chronology pair and their distance apart which was significant (the curve was: Y=0.691-0.011X, r=-0.340, n=91, p<0.001; the maximum distance between the sites was only about 14km). The results in this thesis showed that only with a large sample size over a wide geographic distribution was any trend discernable. The lack of a significant pattern by Ahmed & Ogden (1985) for *Agathis australis* may be a constraint imposed by the species more limited geographic distribution. However the significant regression from *Nothofagus solandri* (Norton, 1983a) would tend to imply that the response is highly variable and species specific.

In general no clear relationship was observed between ring-width and altitude for Kauri (*Agathis australis*) (Ahmed & Ogden, 1985). Norton (1983a) reported a general reduction of autocorrelation, higher mean sensitivity and standard deviation with increasing altitude. The results in this thesis showed that the correlation values have a big range when the altitude is similar. This is possibly because the sites are from very different latitudes and longitudes and other environmental fators (such as rainfall) have a stronger influence (Figure 4.5).

Most of sites from the central North Island were grouped in one group which included TOA, TOB, TOC, HIT, TKP, CLW, OHT and RUC (Figure 4.7). Group B was representative of west coast sites in the North Island and includes sites EMT, NET, STR and MWO. South Island site FLG was also in this group. Site RUH, CRG, MOA, UWR, ARM were in group C. Most of these sites are from the east coast of the South Island but UWR was a North Island east coast site. All the site in group D (AHA, TRK, CRC and WBF) were from West Coast of South Island.

The statistics were very similar for all of the chronologies developed using different sized trees. The correlation between chronologies developed from the middle sized trees (DBH 50-80cm) was higher than that from small or big trees. The differences between the chronologies (Figure 4.8C, 4.9C & 4.10C) were greater in the earlier period than in the later period. This is because of the relatively small number of samples used in the early period. In site TOC, the difference in the later period of the chronology was also greater than that of the middle period. This may be only the influence of size.

4.5 Chapter conclusions

1. Comparison of the chronologies showed a highly consistent and significantly correlated pattern between most of the sites.

2. There was a high linear relationship between the correlation coefficient and log transformed separation distance. The spectral and coherence analyses showed that there were similar cycles when the sites were closer together.

3. A simple linear regression could be applied to the relationship between the correlation coefficient and the difference of altitude. There was a lower cross-correlation between sites as the separation became larger.

4. All 23 chronologies could be grouped into four groups based on the loadings of the first three PCs. These four groups reflected well the geographical position of the sites.

5. Chronologies from 'small' trees may be different with chronologies for the same period from 'big' trees at the same site. This may be due to different responses to climate with age. A good chronology should include a range of different sized trees from the same site.

CHAPTER FIVE

CHRONOLOGICAL CLIMATE SIGNALS

5.1 Introduction

Only in ideal cases, do tree-rings respond to a single climate variable (such as growing season temperature, summer rainfall, etc.). The general tree-climate relationship is so complex that the climate 'signal' can only be extracted from tree-ring data by fairly sophisticated techniques (Fritts *et al.* 1971). The procedure that estimates the statistical growth-environment relationship is called calibration. In palaeoclimatology, calibration involves the fitting of a statistical equation or model that can be applied to one or more predictors to estimate or reconstruct one or more predictands. If climate is the predictor and tree-ring variation is the predictand, then the equation is referred to as a response function. In a response function, the magnitude and the signs of the coefficients of the statistical equation indicate the importance of the tree-ring response to the calibrated variables of climate (Cook & Kairiukstis, 1990).

This chapter investigates the relationships between ring-width and climate data. The first section discusses the different types of climate data used and this is followed by the response function analysis. The bootstrap response function in PRECON (Fritts, 1994) was compared with the general response function. Various climate variables and time spans have been employed due to insufficient information about the phenology / physiology of this species (refer to Chapter 2 and Appendix 1). After this, response function analyses were carried out and the results compared and summarised. A stochastic response function (Kalman filter) (Cook, 1994) was also discussed in this chapter so as to determine how the tree's response to climate may have changed over time.

5.2 The climate data

Meteorological data were examined from stations located throughout New Zealand. The selection of stations was made on the length and completeness of records, as well as proximity to the chronology sites. A minimum climatic record length of 42 years was used based on the recommendation of Blasing *et al.* (1981). Figure 5.1 and Table 5.1 show the positions of climate stations and chronology sites. Climate records with more than five percent of their data missing were excluded (Ogden & Ahmed, 1989). Most dendroclimatic studies have simply used mean-daily

Table 5.1 Summary information about the meteorological stations used in the response function analysis.

Station	Index	Start of record	Latitude	Longitude	Altitude (m)	Annual Total Rainfall (mm)	Annual Mean Temp. (°C)
North Island							
Kaingaroa Forest	B86451	1914	38°24'	176°34'	544	1471	10.74
Taumarunui	C85821	1913	38°52'	175°16'	171	1438	12.18
New Plymouth	C94001	1864	39°04'	174°04'	49	1558	13.61
Chateau, Mt Ruapehu	C95251	1929	39°12'	175°32'	1119	2787	7.21
Waikaremoana Onepoto	D87811	1922	38°48'	177°07'	643	2035	11.18
Napier	D96591	1862	39°30'	176°55'	2	820	14.14
Palmerston N DSIR	E05363	1928	40°23'	175°37'	34	980	12.98
Taihape Rec	E95681	1906	39°41'	175°48'	433	930	10.45
South Island							
Hokitika	F20791	1866	42°43'	170°59'	39	2849	11.53
Motueka DSIR	G12191	1943	41°06'	172°58'	8	1387	12.42
Golden Downs Forest	G12581	1929	41°33'	172°53'	274	1296	10.45
Nelson	G13231	1883	41°17'	173°14'	2	975	12.50
Hanmer Forest	G22581	1905	42°31'	172°51'	387	1148	10.23
The Hermitage Mt Cook	H30711	1901	43°44'	170°06'	765	4148	8.50
Christchurch	H32561	1864	43°32'	172°37'	7	653	11.61
Dunedin BTL Gardens	I50852	1852	45°51'	170°31'	73	944	10.81

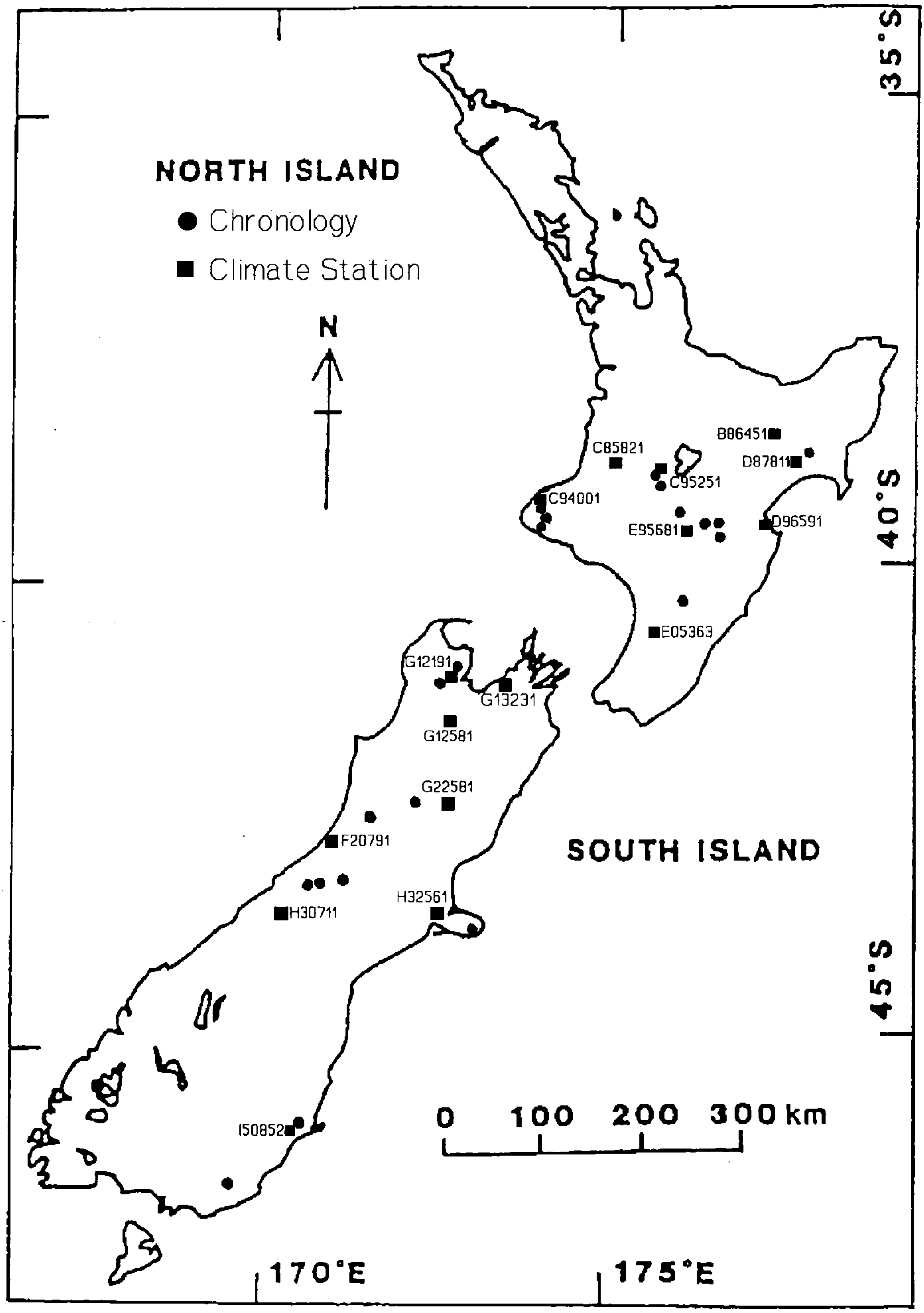


Figure 5.1 The location of chronologies and climate stations.

Table 5.2 Cross-correlations between the different meteorological stations

a) Average November-March temperature (analysis period: 1936-1993, number of observation = 58, except I50852 = 41)*

	B86451	C94001	C95251	D87811	D96591	E05363	E95681	F20791	G12581	G13231	G22581	H30711	H32561	I50852
B86451	1.0000													
	.0000													
C94001	.8072	1.000												
	.0001	.0000												
C95251	.7307	.8822	1.000											
	.0001	.0001	.0000											
D87811	.8631	.7997	.7032	1.000										
	.0001	.0001	.0001	.0000										
D96591	.7388	.7562	.4185	.8112	1.000									
	.0001	.0001	.0011	.0001	.0000									
E05363	.8396	.9166	.6230	.8309	.8665	1.000								
	.0001	.0001	.0001	.0001	.0001	.0000								
E95681	.6334	.6628	.6333	.6606	.6593	.6471	1.000							
	.0001	.0001	.0001	.0001	.0001	.0001	.0000							
F20791	.6020	.8628	.6476	.6324	.5819	.8432	.6144	1.000						
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0000						
G12581	.8100	.9007	.8800	.7997	.5785	.7908	.6601	.7842	1.000					
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0000					
G13231	.7239	.8697	.4119	.7385	.8081	.8849	.6562	.7347	.6614	1.000				
	.0001	.0001	.0013	.0001	.0001	.0001	.0001	.0001	.0001	.0000				
G22581	.7833	.7671	.6011	.8561	.8272	.8687	.6768	.7154	.7542	.8015	1.000			
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0000			
H30711	.6235	.7726	.8260	.5888	.3042	.5677	.5750	.6671	.8636	.4592	.6039	1.000		
	.0001	.0001	.0001	.0001	.0202	.0001	.0001	.0001	.0001	.0003	.0001	.0000		
H32561	.7362	.7455	.7637	.7633	.8081	.8008	.5843	.6486	.7407	.6761	.8389	.6913	1.000	
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0000	
I50852	.5955	.7726	.7202	.6488	.7179	.8107	.4582	.7443	.7293	.6241	.7462	.5947	.8082	1.000
	.0001	.0001	.0001	.0001	.0001	.0001	.0026	.0001	.0001	.0001	.0001	.0001	.0001	.0000

* Station C85821, G12191 not included in this table due to their relatively short temperature records.

Table 5.2 Continued

b) Total November-March rainfall (analysis period: 1931 - 1991, number of observation = 61)*

	B86451	C85821	C94001	C95251	D87811	D96591	E05363	E95681	F20791	G12581	G13231	G22581	H30711	H32561	I50852
B86451	1.000														
	.0000														
C85821	.5244	1.000													
	.0001	.0000													
C94001	.3025	.5024	1.000												
	.0178	.0001	.0000												
C95251	.3939	.7382	.4254	1.000											
	.0017	.0001	.0006	.0000											
D87811	.4274	.0505	-.0575	.0377	1.000										
	.0006	.6993	.6597	.7728	.0000										
D96591	.0583	.0675	-.0257	.0027	-.0721	1.000									
	.6557	.6051	.8441	.9836	.5806	.0000									
E05363	.2861	.5867	.4892	.6810	-.0908	.0468	1.000								
	.0254	.0001	.0001	.0001	.4863	.7204	.0000								
E95681	.0451	.0186	.1617	.1974	-.1123	.3646	.2031	1.000							
	.7303	.8870	.2132	.1272	.3889	.0039	.1164	.0000							
F20791	-.0979	.3467	.0846	.2865	-.3943	.2115	.1904	.3034	1.000						
	.4527	.0062	.5171	.0252	.0017	.1018	.1416	.0175	.0000						
G12581	.5041	.6054	.3092	.4275	.1076	.2474	.4263	.2004	.4026	1.000					
	.0001	.0001	.0153	.0006	.4092	.0546	.0006	.1216	.0013	.0000					
G13231	.4492	.3577	.2316	.2537	.2773	.1190	.2597	.0215	.1666	.7516	1.000				
	.0003	.0046	.0725	.0485	.0305	.3611	.0433	.8692	.1995	.0001	.0000				
G22581	.1902	.3532	.1923	.4405	.1953	-.0946	.5087	-.0088	.0127	.2988	.3411	1.000			
	.1421	.0052	.1376	.0004	.1315	.4684	.0001	.9466	.9228	.0193	.0071	.0000			
H30711	.0588	.4013	.1314	.4084	-.2681	.0969	.2748	.1010	.6260	.1576	-.0438	.2116	1.000		
	.6524	.0014	.3127	.0011	.0367	.4577	.0321	.4385	.0001	.2250	.7376	.1016	.0000		
H32561	.1180	.2973	.2027	.3400	.0361	-.0001	.4335	-.0049	.0484	.2875	.2949	.7482	.1280	1.000	
	.3653	.0200	.1172	.0073	.7823	.9993	.0005	.9699	.7111	.0246	.0211	.0001	.3257	.0000	
I50852	.0010	.2733	.1645	.2260	-.0571	.0811	.3099	.0334	.3007	.2542	.1778	.5133	.3110	.4542	1.000
	.9393	.0331	.2053	.0799	.6619	.5345	.0151	.7981	.0186	.0481	.1704	.0001	.0147	.0002	.0000

* Station G12191 not included in this table due to their relatively short rainfall records.

temperature and monthly rainfall for determining the response function of the chronology / species. In this study, a diverse range of parameters were screened including: monthly rainfall, monthly number of rain days, monthly mean-daily temperature, monthly mean-daily maximum temperature, monthly mean-daily minimum temperature, monthly total sunshine hours and mean vapour pressure.

The similarity between the different meteorological stations was investigated by taking the average temperature (Nov.-Mar.) and total rainfall (Nov. -Mar.). This effectively removed any bias in the cross-correlations due to seasonal changes. The cross-correlation values between the climate stations for the summer growing seasons showed that all of the stations were very similar for temperature but not rainfall (Table 5.2). This result was not surprising since New Zealand has a diverse landform which strongly affects the rainfall pattern (Salinger, 1980).

5.3 Response function analysis

5.3.1 Details of response function analysis

A model is a simplified picture of a functional relationship used to solve a problem (Jorgensen, 1986). The response function in this case relates ring-widths from a single site chronology to previous growth (up to 3 years previously) and to monthly precipitation and temperature values:

$$\begin{aligned} W_i = {} & a_1W_{i-1} + a_2W_{i-2} + a_3W_{i-3} \\ & + b_1T_1 + b_2T_2 \ldots + b_kT_k \ldots + b_{N/2}T_{N/2} \\ & + c_1R_1 + c_2R_2 \ldots + c_kR_k \ldots + c_{N/2}T_{N/2} \end{aligned} \qquad (5.1)$$

where W_i is a standardised tree-ring chronology value for year i, and T_k and R_k are monthly temperature and rainfall values back to N/2 months prior to the end of the growing season (N is usually 28, N could be 48 in the new version of PRECON,).

The obvious way to calculate the response function (i.e. the coefficients b_k and c_k) is to use a stepwise multiple linear regression. However, when calculated in this direct way, the coefficients tend to be unstable; they show considerable variation from step to step in the regression analysis because of intercorrelations in the climate data

(Gray *et al.* 1981). To overcome this, Fritts *et al.* (1971) principal employed component analysis, and replaced equation (5.1) by:

$$W_i = a_1W_{i-1} + a_2W_{i-2} + a_3W_{i-3} + d_1V_1 + d_2V_2 \ldots + d_kV_k \ldots + d_NV_N \qquad (5.2)$$

Here V_k are the eigenvectors of temperature and rainfall [*i.e.* each V_k is a linear combination of the variables T_k (k = 1, ..., N/2) and R_k (k = 1, ..., N/2)]. This is not a completely consistent method, since, although the V_k are orthogonal, the previous growth terms are not. It does, however, appear to overcome the stability problem noted above. When the regression is terminated, the V_k are transformed back to the appropriate T_k and R_k. The transformed coefficients are then the elements b_k and c_k of the response function. If all of the principal components are retained and the regression analysis is carried through to completion, the results of equation 5.1 and 5.2 must be identical.

As with all regression methods, the main problem with the above procedure is testing the significance of the coefficients and the stability of the estimates. In addition, the response function obtained for a dendrochronological sample should be tested by applying it to growth values over years independent of those used for calibration. The most straightforward way to assess the stability is to divide climatic and tree-ring data into a dependent calibration set and an independent verification set (Fritts, 1976). If the estimated tree-ring indices of the independent data, using the regression coefficients calibrated on the dependent data set, are close to the observations, then the response function is judged to be reliable.

Gordon *et al.* (1982) set out the problem of verifying the predictive ability of a model calibrated on one data set when applied to another data set. Because regression coefficients are fitted only to the dependent data, they result in overconfidence in the predictive power of the model. This can be shown by simulating tree-ring indices by random numbers and by calculating response functions with real climatic data (Guiot, 1981; Cropper, 1985). These authors showed that response functions of tree-ring series obtained by simulation had fewer significant regression coefficients than those judged significant by standard student 't' test. This is mainly due to an inadequate number of degrees of freedom. To test regression coefficients, the student 't' test involves n-k-1 degrees of freedom where n is the number of observations and k the number of regressors. If k is set to the number of principal components actually introduced in the regression on the basis of their correlation with the predictand (stepwise regression), the significance of the coefficients is overestimated, because the number k should have been chosen by *a priori* considerations, i. e. by considerations independent from the predictand. A good practice is to select a relatively large number of principal components taking into account 90 or 95% of the variance of the climatic data or to use the PVP criterion of Guiot (1981; 1985). The number k is then the number of principal components selected by an *a priori* criterion, not the number of variables entered into the stepwise regression.

The bootstrap procedure of Efron (1979) provides an alternative approach to test the significance and stability of the regression coefficients within a specific time period. Such an approach has been applied to response functions of tree-ring data by Guiot (1990) and Till & Guiot (1990).

The bootstrap response function in PRECON (Fritts, 1994) was used in this study. In the bootstrap response function, the lack of information on the statistical properties of the data is replaced by a large number of estimates each based on different sub-samples of data. A comparison of these sub-sample estimates is used to assess the variability of the estimates. The sub-sampling is done by random extraction with replacement from the initial data set. The size of each sub-sample is the same as the number of observations in the initial data set (n), thus avoiding bias (Efron, 1983). Each sub-sample forms a bootstrap test used for cross-validation. Guiot (1990) has shown that after 50 sub-samples, the results do not change significantly.

For each sub-sample, the regression coefficients and the multiple correlation are computed on the observations randomly selected (some observations of the initial data set are selected several times in the random selection process, others are absent). An independent verification is done on the unselected observations in each sub-sample. If it is done 50 times, 50 sets of regression coefficients, 50 multiple correlations and 50 independent verification correlations are obtained. The means of the regression coefficients, the multiple correlations, and the independent correlations with their respective standard deviations are computed using these 50

estimates. The bootstrapped regression coefficients are judged significant at the 95% level, if they are twice, in absolute value, their standard deviation (Guiot, 1991; Fritts and Dean, 1992).
The above response function is based on three assumptions: (1) every year exactly one tree ring is formed; (2) the uniformitarian principle holds: i. e. the relevant relations between meteorological and biological processes did not change through time; (3) the principle of limiting factors holds: i. e. growth rate is determined by the most limiting factor.

Another important question in response function analysis is how to account for the persistent effects of the previous seasons climate on current growth (i. e. lag effects). Various approaches have been adopted (Berger *et al.* 1979; LaMarche & Pittock 1982) and are available as options in the program PRECON (Fritts, 1994). Comparative studies by Guiot *et al.* (1982a, 1982b) suggested that these different methods may not however significantly alter the conclusions. The strength of the lag signal can vary through time (Murphy & Palmer, 1992) so the practise of applying the same lag filter used to develop the response model to the period used for climate reconstruction may lead to spurious results. The best approach is to "deautocorrelate" the whole chronology first using an autoregressive filter, and then model its response to climate parameters. This not only avoids the problems mentioned earlier but also eliminates the need to include lags in the response function analysis (Palmer, 1989). In the following response function analysis, only residual chronologies which have been deautocorrelated were used. The only use of residual chronology was further confirmed by the analysis of using different types of chronologies.

5.3.2 Methods

The response function analyses were carried out in the following sequence which was similar with the approach used by Palmer (1989) :

A) Identification of types of climate variables to use

A preliminary study used four chronologies (two from North Island and two from South Island) to identify the best pair of climatic parameters to choose from the following:

Monthly rainfall total
Monthly rain day total
Average monthly daily-mean-temperature
Average monthly daily-maximum-temperature
Average monthly daily-minimum-temperature
Estimated mean monthly solar radiation.
(Table 5.3).

B) Identification of the optimal monthly time-span of response

A preliminary study used the same chronologies and climate stations as above (A) but instead of changing the climate variables, the 14 month period covered by the best pair of climatic parameters was staggered as follows:

January of the previous year to February of the current year
February of the previous year to March of the current year
March of the previous year to April of the current year
April of the previous year to May of the current year
May of the previous year to June of the current year
June of the previous year to July of the current year
July of the previous year to August of the current year
August of the previous year to September of the current year
(Table 5.4).

C) Effect of separation distance between climate stations and chronology sites

A further study examined the relationship of distance between chronology sites and meteorological stations and the associated amount of variance reduced by the response function as shown in Table 5.5.

D) Calibration and verification of response functions with different climate stations

Using the results produced from the above procedures to select the pair of climate variables and their period, the response functions for each chronology with the possible climate stations were calculated and compared (Table 5.6).

E) Summary of significant response functions

The significance of single and overall response functions were discussed and a summary of the significant response functions plotted (Table 5.7 and Figure 5.2). All significant pairs were used to carry out the element matching test (Table 5.8-10) and PCA analysis (Table 5.11 and Figure 5.3-5). In order to confirm the decision of use residual chronology and 14 month time span, 11 sites (group A from the PCA analysis) were picked to compare the response functions between standard chronology and residual chronology. A wider time span (18 months) was used for this analysis (Figure 5.6).

F) Evaluation of climatic factors influencing the response functions

Finally, response functions (RFs) were calculated from combined site chronologies with regionally averaged climatic data based on the above element matching test and PCA analysis. Both linear and curvilinear relationships for the four groups were evaluated with PRECON. Analysis began with the evaluation of simple correlation, multiple regression, and response function techniques. Once a calibration was obtained, a precipitation or temperature change was modelled to occur beginning in the last 50 years by incorporating the change into the instrumental record of precipitation or temperature and recalculating the growth using the calibrated coefficients. Differences between actual and modelled tree growth were used to evaluate which climatic factors could have produced the variations in ring-width (Table 5.12 and Figures 5.7-8).

5.3.3 Results and discussion

A) Comparison of climate parameters

The first three pairs of climate variables for each site in Table 5.3 used rainfall (climate type: 0). This was done to enable the comparison of the different temperature types. The averaged results showed that both monthly mean temperature and monthly mean precipitation have the largest variance reduced. These two types of climate data (2, 0) were used in all further analysis. This selection led to some decrease in the number of significant regressors.

Table 5.3 Comparison of climatic parameters used in response function analysis

Climate/ Chronology	Climate Type[1]	Period	Variance Reduced	#Significant	Proportion[2]
TOA/C95251	2, 0	1931-1993	0.598	3	1, 2
	3, 0	1931-1993	0.580	4	1, 3
	4, 0	1931-1993	0.559	3	1, 2
	2, 1	1931-1993	0.571	3	2, 1
	3, 1	1931-1993	0.538	2	1, 1
	4, 1	1931-1993	0.503	1	1, 0
UWR/D87811	2, 0	1936-1993	0.656	4	1, 3
	3, 0	1936-1993	0.581	5	1, 4
	4, 0	1936-1993	0.572	3	0, 3
MOA/G12581	2, 0	1931-1992	0.590	2	2, 0
	3, 0	1931-1992	0.586	5	4, 1
	4, 0	1931-1992	0.528	3	2, 1
RUH/G22581	2, 0	1907-1992	0.356	0	0, 0
	3, 0	1907-1992	0.257	0	0, 0
	4, 0	1907-1992	0.352	3	3, 0
	9, 0	1931-1992	0.271	0	0, 0

Note:

1. Climate data type codes where:
   - 0 = monthly rainfall total
   - 1 = monthly rain day total
   - 2 = average monthly daily-mean-temperature
   - 3 = average monthly daily-maximum-temperature
   - 4 = average monthly daily-minimum-temperature
   - 9 = estimated mean monthly solar radiation.
2. The proportion of the significant monthly regressors that relate to each type of climate data e.g. for the first line, 1 was from monthly daily-mean temperatures and 2 were from monthly rainfall total.

Table 5.4 Comparison of varying annual spans of climate data used in response functions

Chronology / Climate station	Climate Period From	To	Variance reduced	#Significance	Proportion
TOA/C95251	Jan.	Feb.	.547	3	1, 2
	Feb.	Mar.	.598	4	1, 3
	Mar.	Apr.	.557	3	1, 2
	Apr.	May.	.585	3	1, 2
	May	June	.578	4	2, 2
	June	July	.530	3	1, 2
	July	Aug.	.530	3	1, 2
	Aug.	Sep.	.490	2	1, 1
UWR/D87811	Jan.	Feb.	.629	4	1, 3
	Feb.	Mar.	.656	4	1, 3
	Mar.	Apr.	.611	5	2, 3
	Apr.	May	.577	3	1, 2
	May	June	.501	2	1, 1
	June	July	.454	3	1, 2
	July	Aug.	.520	3	1, 2
	Aug.	Sep.	.506	3	1, 2
MOA/G12581	Jan.	Feb.	.556	5	4, 1
	Feb.	Mar.	.590	2	2, 0
	Mar.	Apr.	.574	3	3, 0
	Apr.	May	.628	2	2, 0
	May	June	.570	1	1, 0
	June	July	.554	0	0, 0
	July	Aug.	.502	1	1, 0
	Aug.	Sep.	.491	2	2, 0
WBA/H30711	Jan.	Feb.	.621	5	3, 2
	Feb.	Mar.	.605	5	3, 2
	Mar.	Apr.	.539	3	2, 1
	Apr.	May	.465	3	2, 1
	May	June	.370	0	0, 0
	June	July	.365	0	0, 0
	July	Aug.	.383	0	0, 0
	Aug.	Sep.	.378	0	0, 0
Combine	Jan.	Feb.	.581	9	5, 4
	Feb.	Mar.	.594	6	4, 2
	Mar.	Apr.	.569	11	7, 4
	Apr.	May	.511	8	5, 3
	May	June	.420	5	2, 3
	June	July	.370	3	1, 2
	July	Aug.	.353	5	3, 2
	Aug.	Sep.	.355	6	5, 1

B) The optimal annual span

The next step was aimed at indicating the optimal 14 months span to use in the response functions (Table 5.4). Of the eight periods tested, the highest amount of explained variance was that from February to March. However, the periods January to February, March to April and April to May had higher numbers of significant monthly regressors. The decision was made to select for the greater variance reduced rather than number of significant regressors.

C) The effect of distance between climate station and chronology

Table 5.5 illustrates the relationship between the amount of variance reduced by response function and the distance the climate station is located from the chronology site. There is no significant relationship between separation distance and the variance reduced.

Table 5.5 Comparison of response functions using climate data from stations at varying distances from the chronology site.

Chronology / Climate	Distance (km)	Period	Variance reduced	#Significant	Proportion
TOA / C95251	8	1931 - 1993	0.598	3	1, 2
TOA / C85821	52	1948 - 1993	0.615	2	1, 1
TOA / E95681	58	1912 - 1993	0.501	3	1, 2
TOA / E05363	126	1929 - 1992	0.547	2	0, 2
TOA / C94001	128	1923 - 1992	0.521	3	2, 1
TOA / D87811	150	1936 - 1993	0.593	1	1, 0
Correlation of "distance" with "variance reduced" = -0.241 NS					
TOA / NZ Average		1894 - 1992	0.562	7	6, 1
MOA / G12191	16	1957 - 1992	0.764	5	3, 2
MOA / G13231	46	1894 - 1992	0.386	2	1, 1
MOA / G12581	66	1931 - 1992	0.582	3	3, 0
MOA / G22581	166	1907 - 1992	0.358	3	3, 0
MOA / H32561	284	1894 -1992	0.310	1	0, 1
MOA / I50852	576	1914 - 1976	0.433	3	1, 2
Correlation of "distance" with "variance reduced" = -0.440 NS					
MOA / NZ Average		1894 - 1992	0.447	8	5, 3

D) Preliminary response function analysis

Table 5.6 shows the results for each chronology site with suitable meteorological data series (two regional and one national average series). The range of variance reduced by the different meteorological data series in the response function was from as little as 0.268 to 0.791. The average correlation coefficients of calibration for all the response functions are significant at the 5% level. The bootstrapped correlation coefficients are judged significant at the 95% level if they are twice, in absolute value, their standard deviation (Guiot, 1991). Thirty response functions verified significantly at the 95% level. But the correlation coefficients and standard deviations of the verification were smaller than those of the calibration. Till and Guiot (1990) pointed out that the loss of precision on the verification data compared to the calibration data results in a lower correlation coefficient and mainly in a higher standard deviation.

Table 5.6 The correlation coefficients of calibration, verification and fractional variance reduced in chronologies by the response function analysis (bootstrap method with 50 replications).

Site	Climate Station	Period	Calibration[1]	Verification[1]	Total[2]	#Significance
EMT	C94001	1923-1988	.797±.048	.310±.150¶	.545	3
	C95251	1931-1988	.843±.054	.282±.190	.588	2
	NZ Ave.	1889-1988	.759±.037	.462±.105¶	.523	6*
NET	C94001	1923-1991	.709±.056	.135±.141	.377	2
	C95251	1931-1991	.818±.045	.284±.176	.542	3
	NZ Ave.	1892-1991	.711±.046	.365±.117¶	.441	6*
STR	C94001	1923-1991	.776±.054	.363±.154¶	.508	4*
	C95251	1931-1991	.801±.053	.345±.181	.558	2
	NZ Ave.	1892-1991	.687±.065	.355±.119¶	.408	8*
TOA	C95251	1931-1993	.842±.031	.380±.172¶	.598	3
	E95681	1912-1993	.754±.036	.383±.126¶	.503	5*
	NZ Ave.	1893-1992	.780±.042	.495±.110¶	.562	5*
TOB	C95251	1931-1993	.845±.043	.415±.179¶	.622	3
	E95681	1912-1993	.744±.044	.316±.112¶	.473	5*
	NZ Ave.	1893-1992	.746±.041	.374±.135¶	.483	7*
TOC	C95251	1931-1991	.792±.059	.249±.146	.496	3
	E95681	1912-1991	.757±.034	.353±.131¶	.489	3
	NZ Ave.	1892-1991	.754±.034	.436±.101¶	.509	6*
MWO	C95251	1931-1977	.867±.050	.194±.214	.570	1
	E95681	1912-1977	.762±.060	.129±.223	.413	1
	NZ Ave.	1889-1977	.737±.047	.280±.117¶	.435	4*
HIT	D96591	1901-1992	.716±.051	.243±.183	.418	3
	E95681	1912-1992	.729±.052	.257±.158	.435	5*
	NZ Ave.	1893-1992	.732±.035	.358±.109¶	.456	10*

OHT	C95251	1931-1992	.777±.062	.199±.216	.513	2
	E95681	1912-1992	.731±.062	.243±.169	.459	3
	NZ Ave.	1893-1992	.711±.041	.329±.113¶	.437	7*
CLW	C95251	1931-1992	.822±.052	.324±.197	.601	4*
	E95681	1912-1992	.735±.051	.238±.188	.441	5*
	NZ Ave.	1893-1992	.652±.049	.206±.122	.343	4*
RUC	C95251	1931-1992	.827±.054	.307±.184	.603	5*
	E95681	1912-1992	.749±.043	.300±.174	.447	4*
	NZ Ave.	1893-1992	.687±.049	.313±.117¶	.402	5*
TKP	E05363	1929-1987	.795±.058	.301±.189	.537	1
	E95681	1912-1987	.745±.046	.345±.181	.485	3
	NZ Ave.	1889-1987	.697±.041	.321±.135¶	.414	3
UWR	B86451	1931-1993	.804±.045	.336±.165¶	.548	4*
	D87811	1936-1993	.869±.037	.413±.144¶	.656	4*
	NZ Ave.	1894-1993	.703±.047	.334±.112¶	.416	6*
MOA	G12191	1957-1992	.961±.025	.299±.214	.772	4*
	G12581	1931-1992	.823±.049	.306±.186	.590	2
	NZ Ave.	1893-1992	.715±.044	.294±.139¶	.432	8*
FLG	G12191	1957-1992	.974±.022	.240±.248	.791	1
	G13231	1894-1992	.697±.042	.253±.119¶	.383	3
	NZ Ave.	1893-1992	.707±.042	.374±.121¶	.431	6*
AHA	F20791	1877-1976	.706±.052	.303±.125¶	.411	3
	G22581	1907-1976	.835±.042	.410±.186¶	.591	5*
	NZ Ave.	1889-1976	.746±.042	.323±.141¶	.458	7*
RUH	F20791	1894-1992	.746±.042	.389±.134¶	.484	8*
	G22581	1907-1992	.701±.060	.086±.176	.356	0
	NZ Ave.	1893-1992	.640±.065	.180±.145	.329	3
ARM	G22581	1907-1941	.965±.028	.135±.273	.753	3
	H32561	1894-1941	.802±.071	-.038±.224	.438	0
	NZ Ave.	1889-1941	.848±.037	.291±.225	.573	4*
WBF	F20791	1894-1993	.677±.046	.172±.120	.362	4*
	H30711	1931-1993	.856±.042	.314±.174	.612	4*
	NZ Ave.	1894-1992	.621±.059	.059±.154	.268	3
CRC	F20791	1894-1979	.725±.040	.321±.110¶	.435	7*
	H30711	1931-1979	.829±.068	.006±.221	.485	1
	NZ Ave.	1889-1979	.648±.057	.041±.129	.327	1
TRK	F20791	1894-1979	.735±.039	.267±.130¶	.429	5*
	H30711	1931-1979	.861±.061	.087±.196	.559	0
	NZ Ave.	1889-1979	.669±.066	.103±.146	.374	2
CRG	H30711	1931-1976	.832±.065	.020±.238	.525	1
	I50852	1914-1976	.750±.054	.043±.193	.398	1
	NZ Ave.	1889-1976	.698±.070	.140±.160	.386	2
OKA	H30711	1931-1976	.859±.056	.123±.245	.536	3
	I50852	1914-1976	.742±.054	.018±.195	.378	2
	NZ Ave.	1889-1976	.673±.064	.107±.157	.349	2

Note:

1 the value is averaged correlation coefficients from 50 replications and their standard deviations.

2 the value is the variance reduced.

¶ Indicates the independent verification of those response functions are significant at 95% level.

* Indicates those response functions accepted at 95% level on the basis of the binomial test of Gray *et al.* (1981).

E) Analysis of significant Response Function elements

a) Single Response Function

In the context of assessing the significance of the total number of significant coefficients in a single response function, Gray *et al.* (1981) have suggested an application of the binomial hypothesis. The following analysis followed the approach used by Briffa (1984). The probability of finding n coefficients significantly non-zero at the 0.05 level in a response function containing N elements is:

$$P = \frac{N!}{(N-n)!n!} p^n q^{N-n} \qquad (5.3)$$

Where: P is the probability

N is the total number of response function coefficients

n is the number of significantly non-zero coefficients

p is the significance level used to determine the probability of a response function coefficient differing from 0

q is (1-p)

Applying this formula to the individual chronologies used in this study (where N = 28, p = 0.05, q = 0.95) the calculation (Equation 5.3) shows that a significant response function is indicated by 4 or more significant coefficients (n = 4, P = 0.037). A total of 33 response functions have at least four non-zero coefficients at the 95% level implying that the overall response function was statistically significant (Table 5.6). However, 10 of the 33 response functions did not verify using independent data (Table 5.6) and this meant only 23 response functions were both verified and significant.

The above discussion of the overall significance of the response function does not take into account the numerical values of the individual coefficients. Suppose a single coefficient is very large and the 95% confidence limits are a long way from the zero line. Such a coefficient would be highly significant, with a probability level α well below 0.05. For N =28, and with only this one very significant coefficient, the overall response function will be significant at the 0.05 level if $\alpha < 0.00187$ and at the 0.01 level if $\alpha < 0.00036$. Thus a response function may be significant either if a few

elements have error bars a long way away from the zero line, or if many elements have error bars only just clear of the zero (Gray *et al.* 1981).
Re-evaluating the rejected response functions with three significant non-zero coefficients and verified by independent data, there were four response functions that had at least one coefficient which was larger than three times their standard deviation in absolute value (e.g. EMT-C94001; Table 5.6). Consequently, 27 response functions were finally selected (Table 5.7).

b) Overall Response Function

The statistically significant response elements were summarised in Figure 5.2. The application of the binomial distribution to determine the overall significance of an individual response function (Gray *et al.* 1981) can be extended to consider the statistical significance of the summary response in any one month to either temperature or precipitation (Gray & Pilcher 1983).

There are 149 significant coefficients (both positive and negative) contained in the 27 response functions (Table 5.7). The probability of any one square in Table 5.7 (27 X 28 grid) containing a positive or a negative sign is therefore p=149/(28 X 27)=0.1971. The probability of obtaining a coefficient of a particular sign is p=149/(28 X 27 X 2) = 0.0985. Therefore, the probability of obtaining n significant coefficients of a particular sign in any one grid of table 5.7 is given by:

$$P_n = \frac{27!}{(27-n)! \times n!} \times 0.0985^n \times 0.9015^{27-n} \qquad (5.4)$$

At least 6 significant coefficients indicate a significant response function (n=6, p=0.0306).

Different p and q values (Equation 5.3) are used to calculate the significance levels of the positive and negative coefficient totals because the number of positive and negative coefficients are very different. This allows for the different observed probabilities of obtaining a positive or a negative coefficient in any square of table 5.7; given that the response function contains 43 of positive sign and 106 of negative sign. The probability of obtaining a single positive coefficient is:

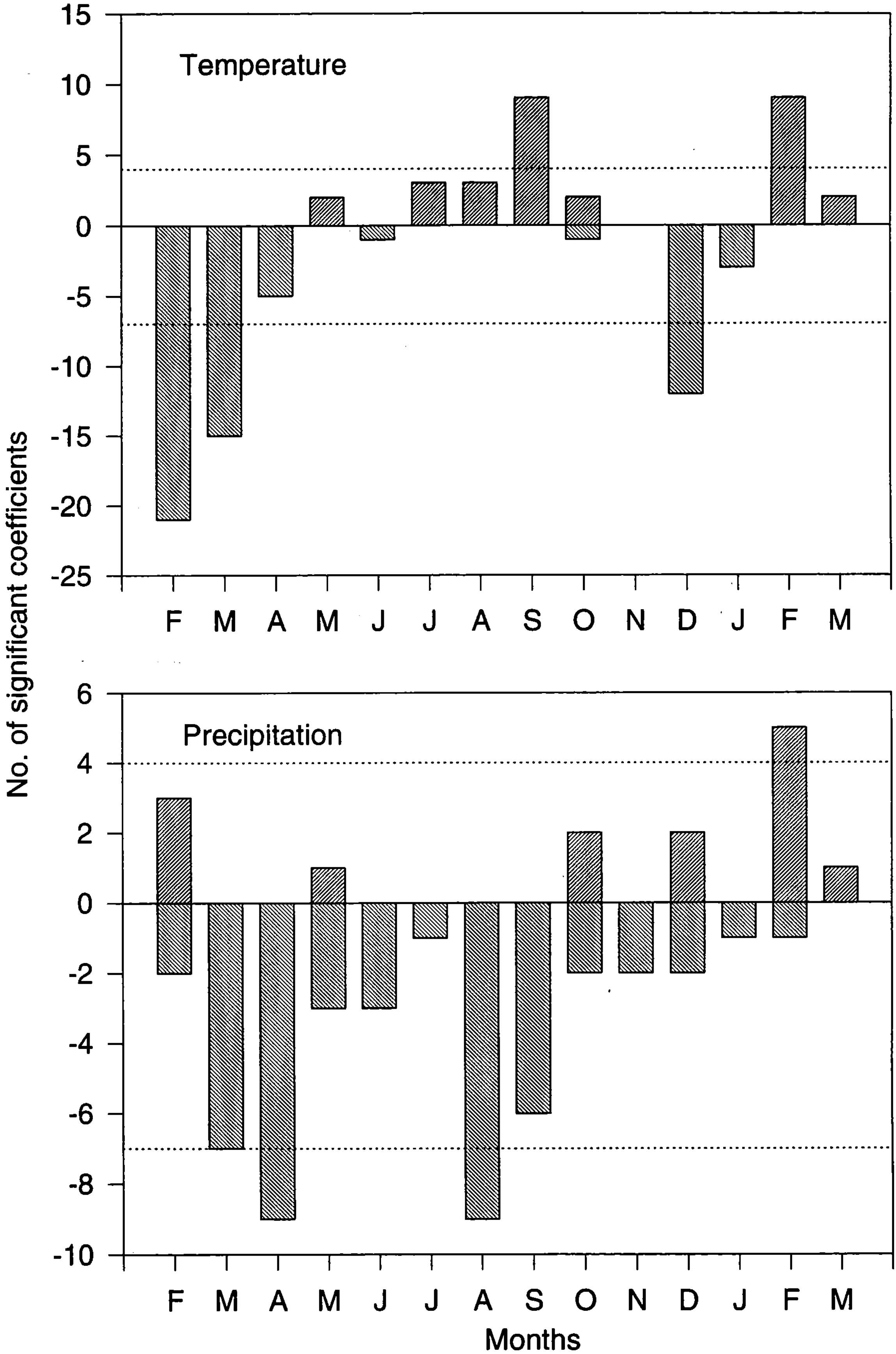


Figure 5.2 The summary response function plot for the 27 significant response functions. The dotted line was the 95% significant level.

Table 5.7 Summary of the significant ($p<0.05$) response function coefficients for the 27 pairs.

Chronology-	Temperature (month)														Precipitation (month)													
Climate Pairs	F	M	A	M	J	J	A	S	O	N	D	J	F	M	F	M	A	M	J	J	A	S	O	N	D	J	F	M
EMT-C94001		-	-														-											
EMT-AVE.	-	-									-					-	-											
NET-AVE.	-							+			-	-				-	-											
STR-C94001		-						+										-			-							
STR-AVE.	-	-		+					+		-		+			-					-							
TOA-C95251	-																			-								+
TOA-E95681	-	-	-										+			-												
TOA-AVE.	-											-				-									-		+	
TOB-E95681	-										-		+			-							-					
TOB-AVE.	-	-						+			-	-				-						-						
TOC-E95681	-																				-		-					
TOC-AVE.	-	-									-		+									-					+	
MWO-AVE.	-																-								+		+	
HIT-AVE.	-	-		+				+			-		+				-		-					-			+	
OHT-AVE.		-						+			-		+		+		-										+	
RUC-AVE.	-	-									-		+		+													
TKP-AVE.	-								+													-						
UWR-B86451	-						+										-		-									
UWR-D87811														+			-	-							-			
UWR-AVE.	-		-				+				-				-		-											
MOA-AVE.	-	-				+					-				+			-			-	-						
FLG-AVE.	-	-	-					+					+						-									
AHA-G22581		-			-													+			-	-						
AHA-AVE.	-	-					+	+			-										-	-						
RUH-F20791	-	-	-					+													-		+	-	+			
CRC-F20791						+			-				+		-						-		+			-		
TRK-F20791	-					+		+													-						-	
Total +	0	0	0	2	0	3	3	9	2	0	0	0	9	1	3	0	0	1	0	0	0	0	2	0	2	0	5	1
Total -	21	15	5	0	1	0	0	0	1	0	12	3	0	0	2	7	9	3	3	1	9	6	2	2	2	1	1	0
Total ±	21	15	5	2	1	3	3	9	3	0	12	3	9	1	5	7	9	4	3	1	9	6	4	2	4	1	6	1

$$p = \frac{43}{27 \times 28} = 0.0569$$

q = 1 - 0.0569 = 0.9431. Applying these to Equation 5.3 (N=27) shows that a significant response function is indicated by 4 or more positive significant coefficients (n=4, p=0.0478). Similarly, 7 or more negative significant coefficients are needed to indicate a significant response function (n=7, p=0.0461). Hence, there are the 0.05 probability levels of 4 and 7 coefficients for the positive and negative coefficient totals respectively (Figure 5.2).

There were 87 significant temperature coefficients of which 29 are positive and 58 negative. Five months exceeded the 0.05 probability level. The prior growth season months of February and March had the largest number of negative coefficients. September (spring month) had a positive significant coefficient. The summer response varied with months: early summer (December) showed negative while late summer (February) was positive. There were 62 significant precipitation coefficients of which only 14 had a positive sign. At the 0.05 level, prior March-April and August showed significant negative values; current February is the only significant positive precipitation month (Figure 5.2).

F) Comparing with other published response functions

There are several response functions already published for New Zealand tree species (Norton, 1984; Ogden & Ahmed, 1989; Palmer, 1989; Salinger *et al.* 1994).

Norton (1984) reported the tree-growth-climate relationships from 21 subalpine *Nothofagus menziesii* and *N. solandri* tree-ring chronologies, and temperature and precipitation variables in the South Island of New Zealand. He found all 21 chronologies showed a positive association with temperature during most of summer months of December to March. Of the 13 significant precipitation regression coefficients during December to March, 12 are negative. The 12 month span June-May and 3 prior growth years were used in his research.

Ogden and Ahmed (1989) carried out climate response function analyses of kauri (*Agathis australis*) tree-ring chronologies located in the northern part of the North Island. The same 12 months span as Norton (1984) with or without 3 prior growth years was used. In the 25 individual response functions, the majority of significant responses to rainfall were negative and the monthly pattern of response was similar whether or not prior growth was included. In the summary response function, significant negative responses relate to rainfall in the previous June, in September and October, and in April at the end of the current growing season. The temperature response functions with prior growth showed about the same number of significant coefficients as for rainfall, but the response functions without prior growth had fewer significant coefficients. As with rainfall, most significant temperature coefficients tended to be negative, but this effect was less clear. When prior growth was included there were significant positive response in July and August, and negative response in November, December and April. Excluding prior growth reversed the trend in July (and April), but not in November and December.

Another response function analysis was done on *Phyllocladus trichomanoides* by Palmer (1989) using sites predominantly located in the central North Island. The 12 month span August-July was used for this research. No prior growth years were used as the autocorrelation in the chronologies was already removed. The response function showed a negative relationship between temperature and growth for the months September, November to December and April to May, while there was a positive response to temperatures in October and February to March. The rainfall response was more variable with distinct alternating pattern during consecutive summer months. However, there was a consistent negative response to August, September and October rainfall.

The most recent published response function was that of 8 chronologies from five species (Salinger *et al.* 1994). March of the previous year to April of the current year and one prior growth year were used for this response function analysis. Seven of the eight chronologies had significant regression weights for temperature over the November to March period. In almost all cases the regression weights were negative. Significant regression weights are also associated with precipitation at most of the sites.

The response function analyses suggested that the different chronologies respond to temperature and precipitation anomalies in different ways at certain times of the year. However, all the chronologies from different species responded to summer temperatures significantly. *Libocedrus bidwillii* also responded to temperature negatively in December and positively in February (Figure 5.2).

The differences among the above discussed response functions may be caused by: (1) The different chronology standardisation techniques employed in the development of chronologies. For example, Ogden and Ahmed (1989) used polynomial curve, Palmer (1989) employed a 50 year Gaussian filter and Salinger *et al.* used a 2/3 cubic spline. This thesis employed a double detrending method (with 2/3 spline filter). Some chronologies already removed autocorrelation [such as Palmer (1989) and this thesis], but most did not. Ogden and Ahmed (1989) proved that the response function could be different when prior growth was or was not included. (2) The chronology geographical differences. Norton (1984) used South Island chronologies; Ogden and Ahmed (1989) used the chronologies from northern part of the North Island; central North Island chronologies were used by Palmer (1989); Salinger *et al.* (1994) and this thesis investigated more widely, from both the North Island and the South Island. (3) Different physiological responses to climate factors due to different species. (4) Different annual spans used in the response function. Due to a lack of physiological understanding of the species, the optimal annual span was selected statistically.

G) Spatial analysis of chronology climate signals

a) Element matching test

Each element of a response function (F_1) was tested against the corresponding element of another response function (F_2). If the 95% error bars overlapped, then a match was designated. The number of non-matches were counted, and the significance tested by exactly the same theory used in determining the overall significance of the response function (Gray *et al.* 1981). Here, n=6 and p=0.0306. Of the 351 possible pairs (Table 5.8) there were 288 that differed significantly.

Table 5.8 Element matching test for all pairs of significant response functions

Site-climate	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
EMT-C94001 (1)	-																										
EMT-AVE. (2)	4	-																									
NET-AVE. (3)	7	3	-																								
STR-C94001 (4)	5	7	8	-																							
STR-AVE. (5)	7	5	8	8	-																						
TOA-C95251 (6)	6	6	7	7	9	-																					
TOA-E95681 (7)	4	4	7	7	5	5	-																				
TOA-AVE. (8)	8	6	5	9	9	6	6	-																			
TOB-E95681 (9)	8	4	5	9	5	6	4	6	-																		
TOB-AVE. (10)	8	4	3	7	7	4	6	6	6	-																	
TOC-E95681 (11)	6	6	7	5	7	7	6	6	4	8	-																
TOC-AVE. (12)	7	5	8	8	6	5	4	6	5	5	7	-															
MWO-AVE. (13)	5	5	6	8	10	11	7	4	7	9	5	6	-														
HIT-AVE. (14)	9	7	8	10	8	8	9	11	9	9	11	6	8	-													
OHT-AVE. (15)	6	5	7	5	9	6	8	10	7	8	9	5	7	5	-												
RUC-AVE. (16)	5	4	7	7	5	4	4	8	4	6	6	3	7	7	4	-											
TKP-AVE (17)	6	6	7	7	7	5	6	6	6	6	4	5	5	11	9	6	-										
UWR-B86451 (18)	5	5	6	8	10	6	7	7	7	9	5	8	4	8	8	7	5	-									
UWR-D87811 (19)	5	7	8	6	12	7	9	6	9	11	7	10	5	12	9	9	7	6	-								
UWR-AVE. (20)	5	5	6	10	9	9	7	9	7	9	7	8	6	10	8	6	7	4	8	-							
MOA-AVE. (21)	9	5	10	6	8	7	9	11	9	7	7	6	10	12	9	5	7	10	10	9	-						
FLG-AVE (22)	5	7	8	6	6	7	3	8	7	7	7	6	8	6	7	5	7	6	10	8	10	-					
AHA-G22581 (23)	6	8	11	4	9	8	8	10	8	8	6	7	9	13	10	8	6	9	8	11	6	9	-				
AHA-AVE. (24)	7	6	7	5	7	8	8	8	8	4	6	5	8	9	8	6	6	7	11	7	5	7	6	-			
RUH-F20791 (25)	7	9	10	6	10	9	7	9	10	9	7	10	8	10	11	9	9	10	11	10	10	6	9	7	-		
CRC-F20791 (26)	10	12	13	9	10	10	10	12	9	14	7	11	11	15	11	9	9	11	11	11	10	11	10	12	11	-	
TRK-F20791 (27)	8	8	7	5	9	6	8	7	8	8	4	8	6	10	9	8	6	7	9	9	7	7	8	6	7	8	-

Note: The number refers to how many regressor element confidence intervals fail to overlap with those from another response function. When five or more mismatches occur (non-bold) the response functions are considered significantly different (following Gray *et al.* 1981 and Palmer 1989).

In order to more clearly identify any pattern specifically associated with either the chronologies or the climate data, the relevant pairs were taken from Table 5.8 and presented separately in Tables 5.9 & 5.10.

Table 5.9 contains 11 comparisons of the same chronologies but using different meteorological stations. Similarly, 112 pairs of the same meteorological data but using different chronologies are shown in Table 5.10. The results of Tables 5.9-10 indicate which of the two variables (meteorological data or chronologies) had the greater variability. There are two chronologies (EMT, UWR) which had similar responses to the different meteorological data. There are also some meteorological data series (C95251, NZ Average) which had similar responses to different chronologies. It was difficult to judge which variable had a greater influence. Consequently, PCA analysis was used and is discussed in the next section.

Table 5.9 A subset of the results from the element matching test (Table 5.8) showing the differences between climate data series using the same chronology. See Table 5.8 for an explanation of the numbers.

Chronology	Climate data	1	2	3
EMT	C94001 (1)	-		
	NZ Average (2)	**4**	-	
STR	C94001 (1)	-		
	NZ Average (2)	8	-	
TOA	C95251 (1)	-		
	E95681 (2)	**5**	-	
	NZ Average (3)	6	6	-
TOB	E95681 (1)	-		
	NZ Average (2)	6	-	
TOC	E95681 (1)	-		
	NZ Average (2)	7	-	
UWR	B86451 (1)	-		
	D87811 (2)	6	-	
	NZ Average (3)	**4**	8	-
AHA	F20791 (1)	-		
	NZ Average (2)	6	-	

Table 5.10 A subset of the results from the element matching test showing the differences between chronologies using the same climate station.

Climate Data	Chrono-logy	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
C94001	EMT (1)	-														
	STR (2)	**5**	-													
E95681	TOA (1)	-														
	TOB (2)	**4**	-													
	TOC (3)	6	**4**	-												
F20791	RUH (1)	-														
	CRC (2)	11	-													
	TRK (3)	7	8	-												
NZ	EMT (1)	-														
Average	NET (2)	**3**	-													
	STR (3)	**5**	8	-												
	TOA (4)	6	**5**	9	-											
	TOB (5)	**4**	**3**	7	6	-										
	TOC (6)	**5**	8	6	**5**	**5**	-									
	MWO (7)	**5**	6	10	**4**	9	6	-								
	HIT (8)	7	8	8	11	9	6	8	-							
	OHT (9)	**5**	7	9	10	8	**5**	7	**5**	-						
	RUC (10)	**4**	7	**5**	8	6	**3**	7	7	**4**	-					
	TKP (11)	6	7	7	6	6	**5**	**5**	11	9	6	-				
	UWR (12)	**5**	6	9	9	9	8	6	10	8	6	7	-			
	MOA (13)	**5**	10	8	11	7	6	10	12	9	**5**	7	9	-		
	FLG (14)	7	8	6	8	7	6	8	6	7	**5**	7	8	10	-	
	AHA (15)	6	7	7	8	**4**	**5**	8	9	8	6	6	7	**5**	7	-

b) PCA analysis

The summary response function and element matching tests merely showed the actual number of significant regressors, not their values (i. e. it did not account for the "distance" of a regressor from the zero line). To further analyse the geographical variations of the response functions described earlier and with the aim of summarising their large variability, a principal component analysis (PCA) was carried out. The regression coefficients of the individual monthly temperature and precipitation variables calculated in the response functions were used as the variables and the realisations of the particular coefficients on each chronology were used as the cases or observations (Briffa, 1984). As the response functions were calculated for 27 response function pairs, each involving 14 temperature and 14 precipitation variables, this PCA was comprised of 28 variables each with 27

observations. Table 5.11 shows that about 72% of the total variance is explained by seven components, indicating that only a moderate degree of common information exists in the data and confirming the spatial complexity of the climate signals in the chronologies. Only the first three components are discussed in detail.

The first three PCs accounted for 42.34% of the total variance. Their weights, together with their relative importance at each site were shown in Figures 5.3-5.5. The number in the figures refers to the response function pairs in Table 5.8.

Table 5.11 The proportion of the total variance explained by the first 10 components in the PCA of response function coefficients for the 27 response functions

PC	%Variance	Cumulative % variance
1	16.72	16.72
2	14.62	31.34
3	11.00	42.34
4	9.59	51.93
5	7.98	59.92
6	6.58	66.50
7	5.52	72.02
8	4.73	76.76
9	3.98	80.74
10	3.36	84.10

PC1 (16.72% of the variance): This pattern (Figure 5.3) has negative temperature loadings in the previous growth season March and April and also in current August, October to January and March. Temperature loadings are positive on all of the months from May to September (except August). Precipitation loadings are similar to temperature in the period from previous February to May and current February and March. All other months are opposite.

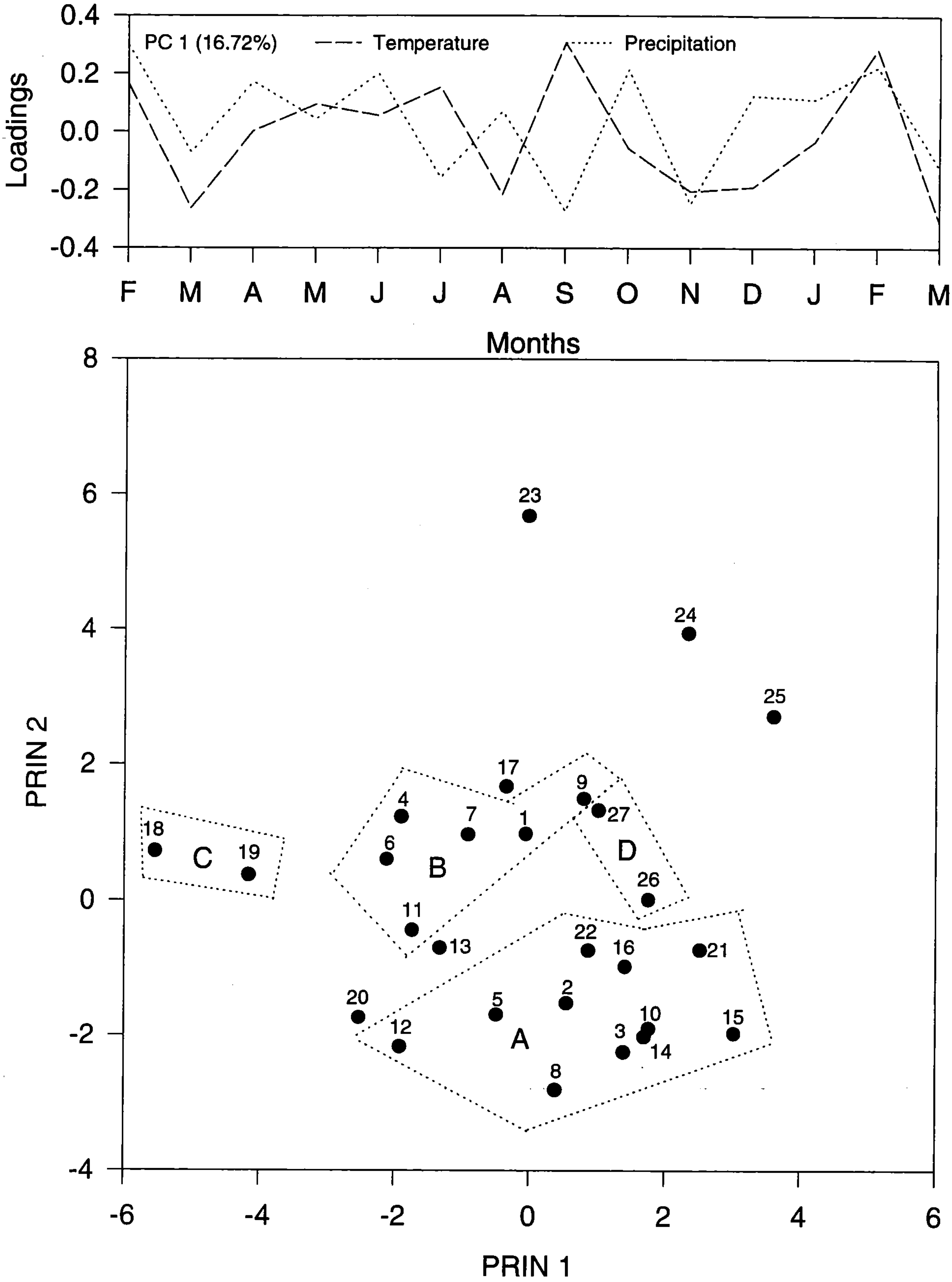


Figure 5.3 The loadings of the first component (above) and the scores of the first and the second component on each response function (bottom).

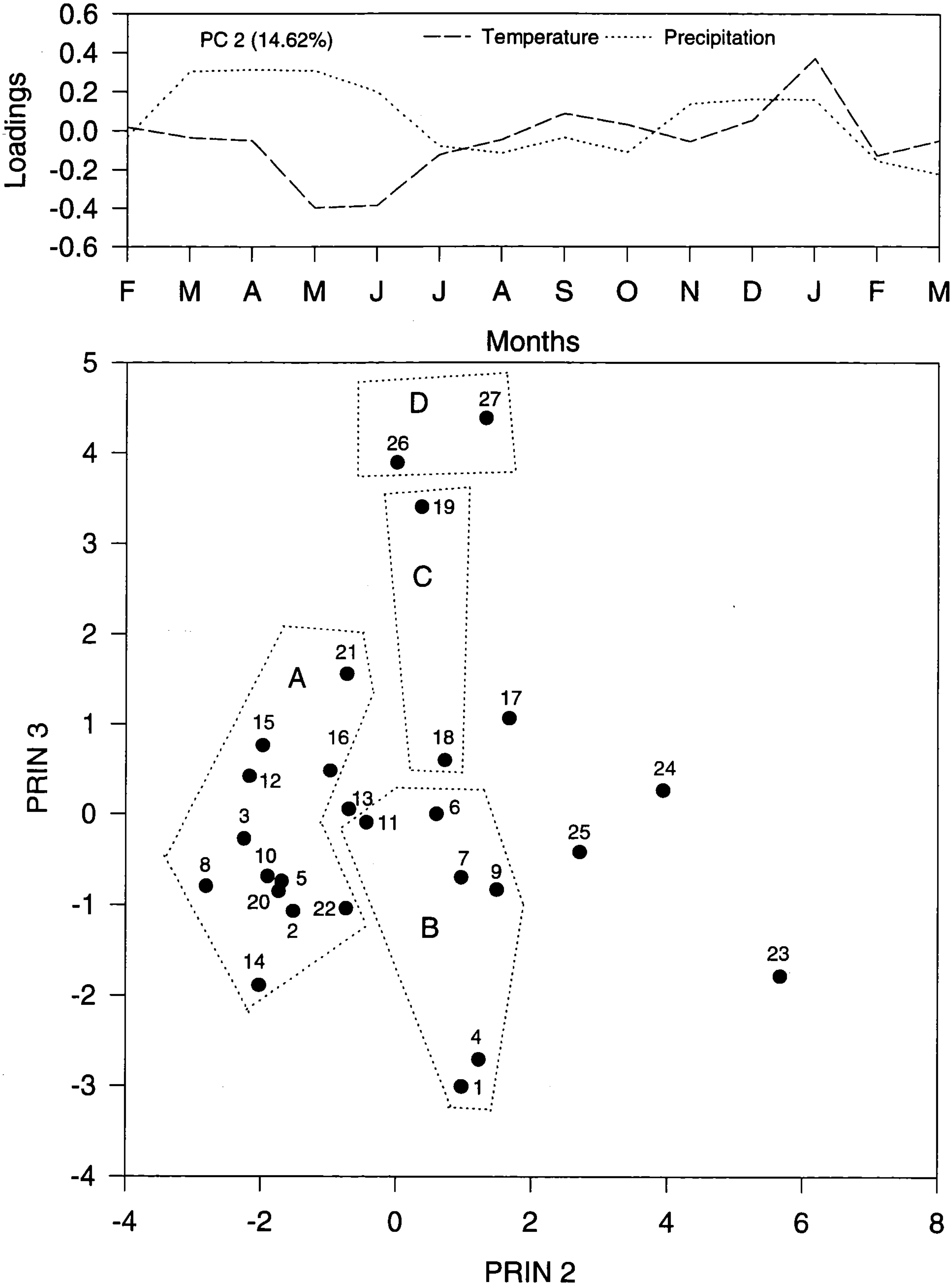


Figure 5.4 The loadings of the second component (above) and the scores of the second and the third component on each response function (bottom).

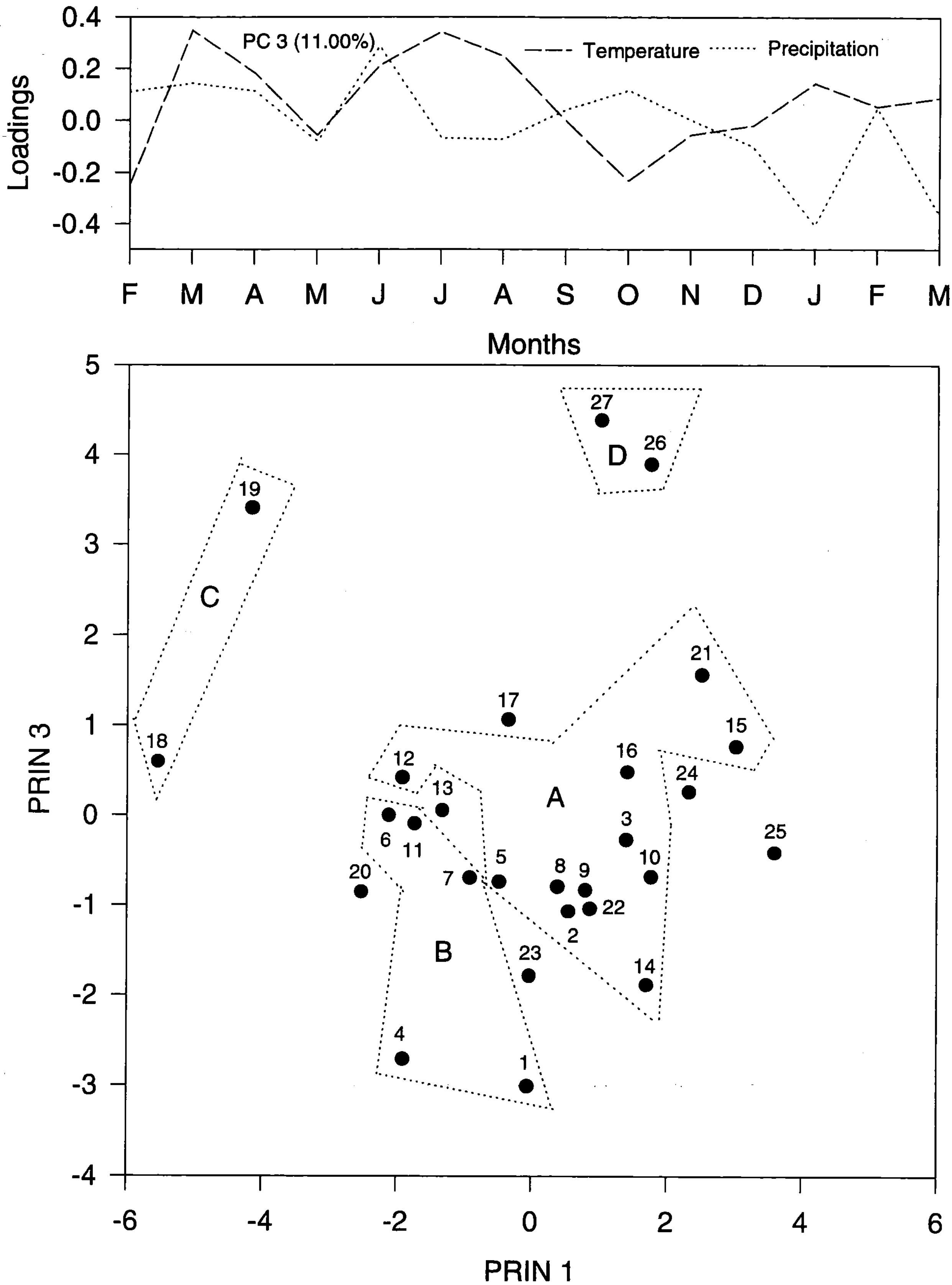


Figure 5.5 The loadings of the third component (above) and the scores of the first and the third component on each response function (bottom).

PC2 (14.62% of the variance): Precipitation loadings are strongly positive from February to June (Figure 5.4). They are followed by nearly zero loadings (July to October) then positive and end at negative values in February and March. Temperature loadings are opposite to precipitation from February to June, but similar from July to March.

PC3 (11.0% of the variance): Unlike PC1 and PC2, temperature loadings of PC3 are positive on all the months except May and October. The trend of precipitation loadings is similar with temperature from March to June but opposite in all other months (Figure 5.5).

The response function pairs can be grouped into four clusters according to their spatial location. The clusters are based on the distance calculated from all the components based on the cluster analysis of SAS package (SAS institute Inc. 1992). Only three are shown in Figures 5.3-5.5. Some response function pairs look like they form one group in one figure but then form another group in another figure. Such an example was response function 13, which first looks like it should be included in Group A from the first three PCs, but from the distance of all PCs, it should not be included in any of the four groups.

(1) Group A includes 11 response function pairs: 2 (EMT-AVE.), 3 (NET-AVE.), 5 (STR-AVE.), 8 (TOA-AVE.), 10 (TOB-AVE.), 12 (TOC-AVE.), 14 (HIT-AVE.), 15 (OHT-AVE.), 16 (RUC-AVE.), 21 (MOA-AVE.), 22 (FLG-AVE.). This group consists of response functions between 11 widely distributed chronologies and the national average meteorological data series.

(2) There are 6 response function pairs in Group B. They are: 1 (EMT-C94001), 4 (STR-C94001), 6 (TOA-C95251), 7 (TOA-E95681), 9 (TOB-E95681), 11 (TOC-E95681). All five chronologies and three climate data series come from the central North Island. This group could be looked on as the central North Island regional representative.

(3) Group C are the response functions (18, 19 in Table 5.8) of east coast chronology UWR with two different regional meteorological stations (B86451 and D87811) in the east coast of North Island.

(4) Group D includes response functions between climate station F20791 and two west coast sites (CRC and TRK) in the South Island.

There are six response functions not in the above groups. They are 13 (MWO-Ave.), 17 (TKP-Ave.), 20 (UWR-Ave.), 23 (AHA-G22581), 24 (AHA-Ave.) and 25 (RUH-F20791). Chronology UWR is already included in one of the response functions in Group C. Because of their unique characteristics, the four chronologies (MWO, TKP, AHA and RUH) will not be discussed further.

H) Confirmation of the chronology standardisation approach and the response function pattern

The eleven sites of Group A (see the above section) and national average climate data were selected to run response function again. However, this time, an 18 month time span (previous January to current June) and standard chronology with prior growth, residual chronology with prior growth were used in addition to the residual chronology without prior growth. The summary of the response functions (RFs) was shown in Figure 5.6. The significance of the summary RFs was tested using the same methods as the above section. There were 2 more significant coefficients in the RFs using residual chronologies than that of standard chronology. The monthly pattern of RFs using residual chronology was similar whether or not prior growth was included. No significant lag effect was left in the residual chronology but a very strong lag effect in the RF of the standard chronology. When an 18 months time-span was introduced in the RFs, no significant coefficients occured after the current March and also no significant coefficients were left in previous January except the precipitation with the standard chronology. These results (more significant coefficients in the residual chronology, no significant lag effect in the residual chronology and no significant coefficients in previous January and after current March in residual chronology) confirmed the use of residual chronologies without prior growth and the 14 months time span (February - March) used in the earlier section of this chapter.

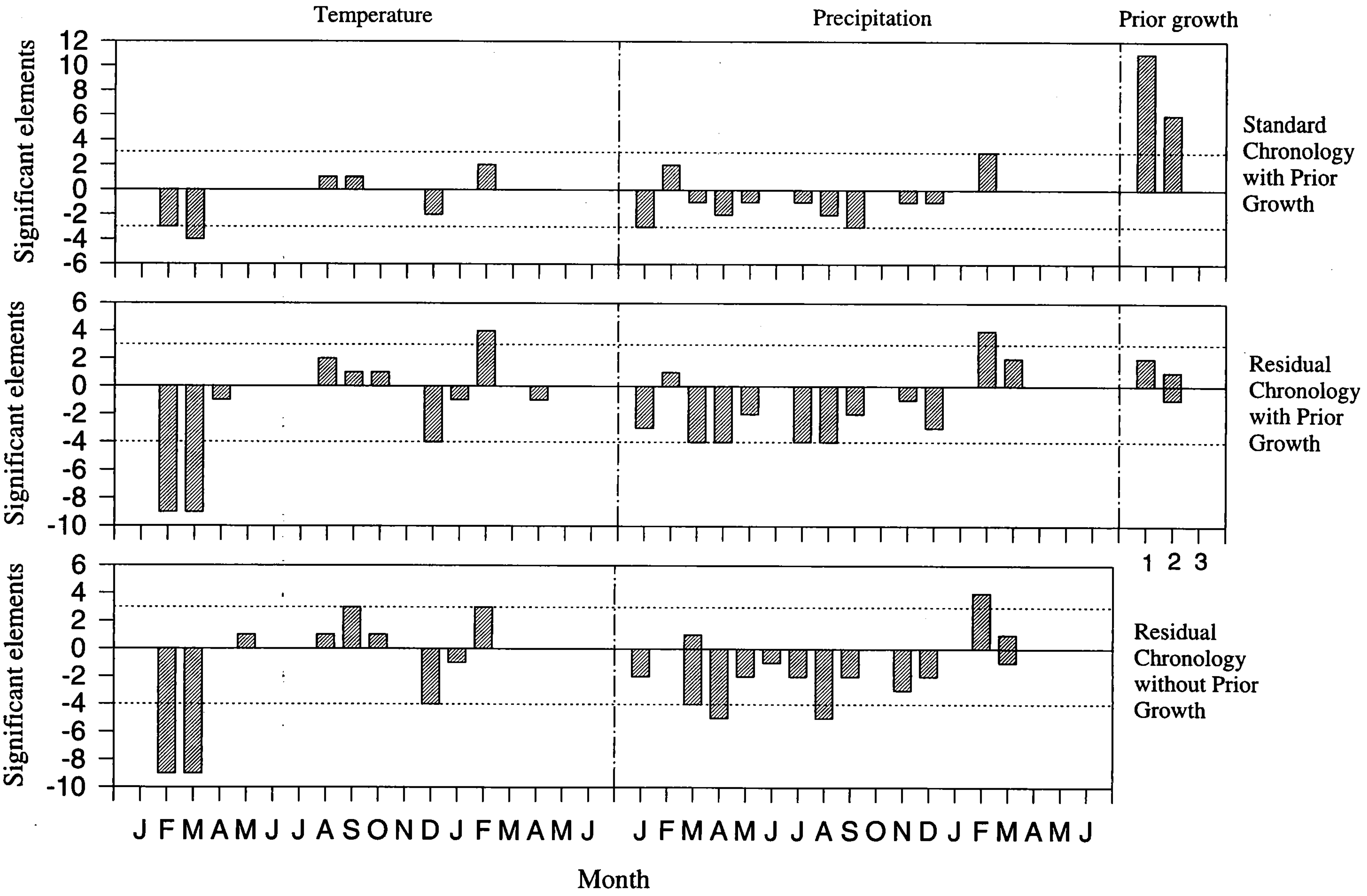


Figure 5.6 The comparison of summary response functions from standard and residual chronologies. The dotted line was the 95% significance level.

5.4 Regional climate signal analysis

5.4.1 Response functions of the four chronology groups

The correlation coefficients for calibration in all four groups (A-D) are significant (Table 5.12). The standard deviations of correlation coefficients in independent verification are less than half of the correlation coefficients in three groups (A, B, D). The verification correlations are significant in these three groups, but, D is near the margin of the significance and the verification value is relatively small compared to the calibration value. Consequently, only groups A and B are discussed in detail.

Table 5.12 The fractional variance reduced in the chronologies by multiple regression analysis, response function analysis, and multiple regression analysis of the interaction.

Group		A	B	C	D
Period		1894-1992	1912-1993	1931-1993	1880-1979
Mult. Reg.[1]		0.462	0.432	0.562	0.226
R	Calib.[2]	0.795±0.036	0.829±0.030	0.836±0.044	0.729±0.044
F	Verif.[2]	0.526±0.106	0.563±0.091	0.340±0.177	0.289±0.134
.	Total[1]	0.576	0.627	0.605	0.429
Interaction[1]		0.327	0.446	0.514	0.253

Note:

A. Group A chronologies (11 sites) with New Zealand average meteorological data.
B. Group B chronologies (5 sites) with the average climate data from stations C94001, C95251 and E95681.
C. Chronology UWR with the average climate data from stations B86451 and D87811.
D. Group D chronologies (sites CRC and TRK) with climate data from station F20791.
RF. Response functions.
1. the value is the variance reduced.
2. the value is the averaged correlation coefficients from 50 replications and their standard deviations.

5.4.2 Group A chronologies and NZ average climate data series

Figure 5.6 shows an analysis of the effects of NZ average monthly temperature and precipitation on the prewhitened (residual) ring-width indices of 11 chronologies in Group A. The fractional variance reduced by the analysis ranged from 0.327 for the interaction to 0.576 for the response function analysis (Table 5.12).

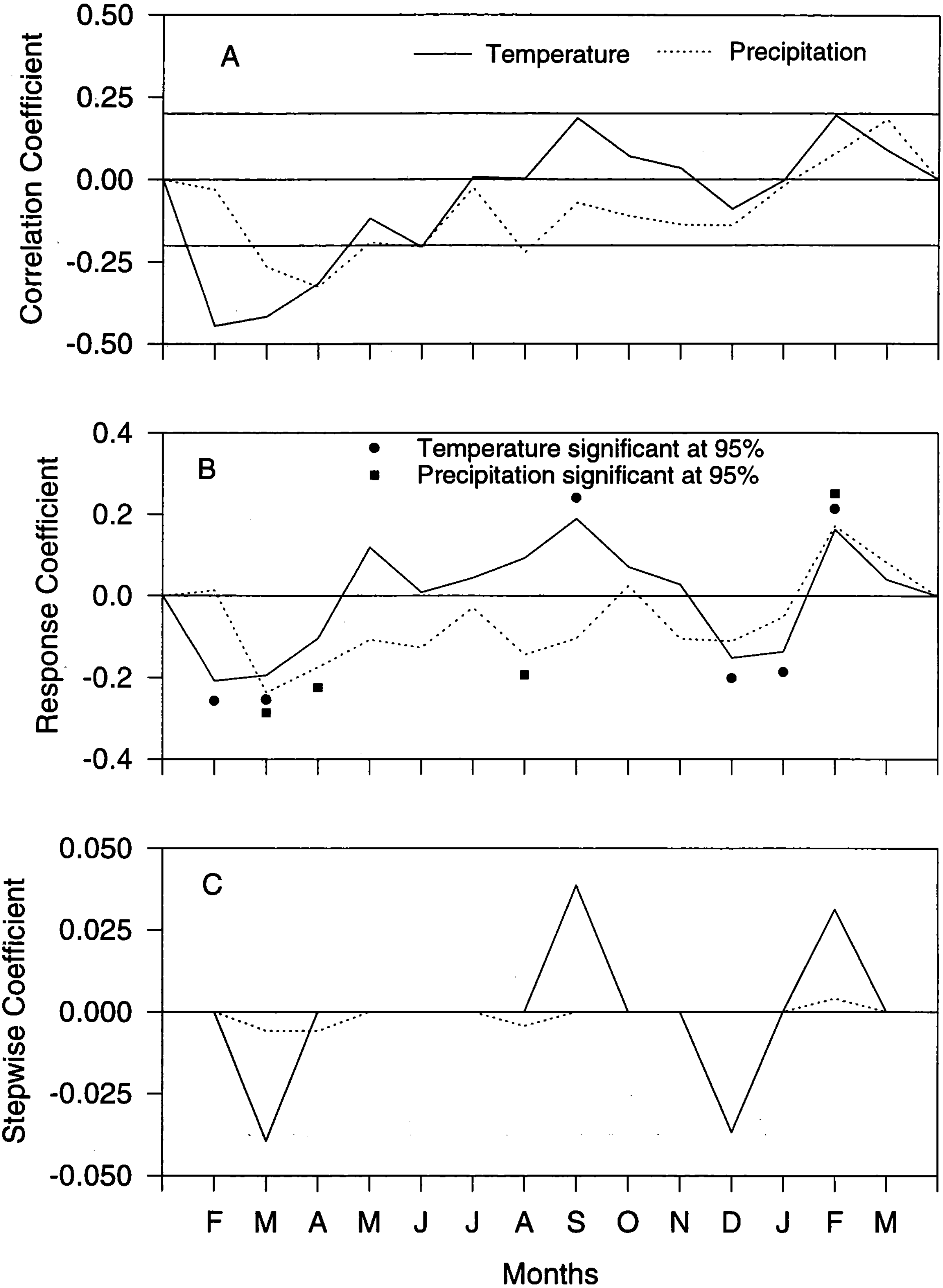


Figure 5.7 Analysis of Group A chronology with NZ average meterological data series. **A.** Simple correlation function. The line at 0.20 indicates significant at 95%. **B.** Bootstrap response function. **C.** Stepwise multiple regression. Coefficient value selected when F > 3.5.

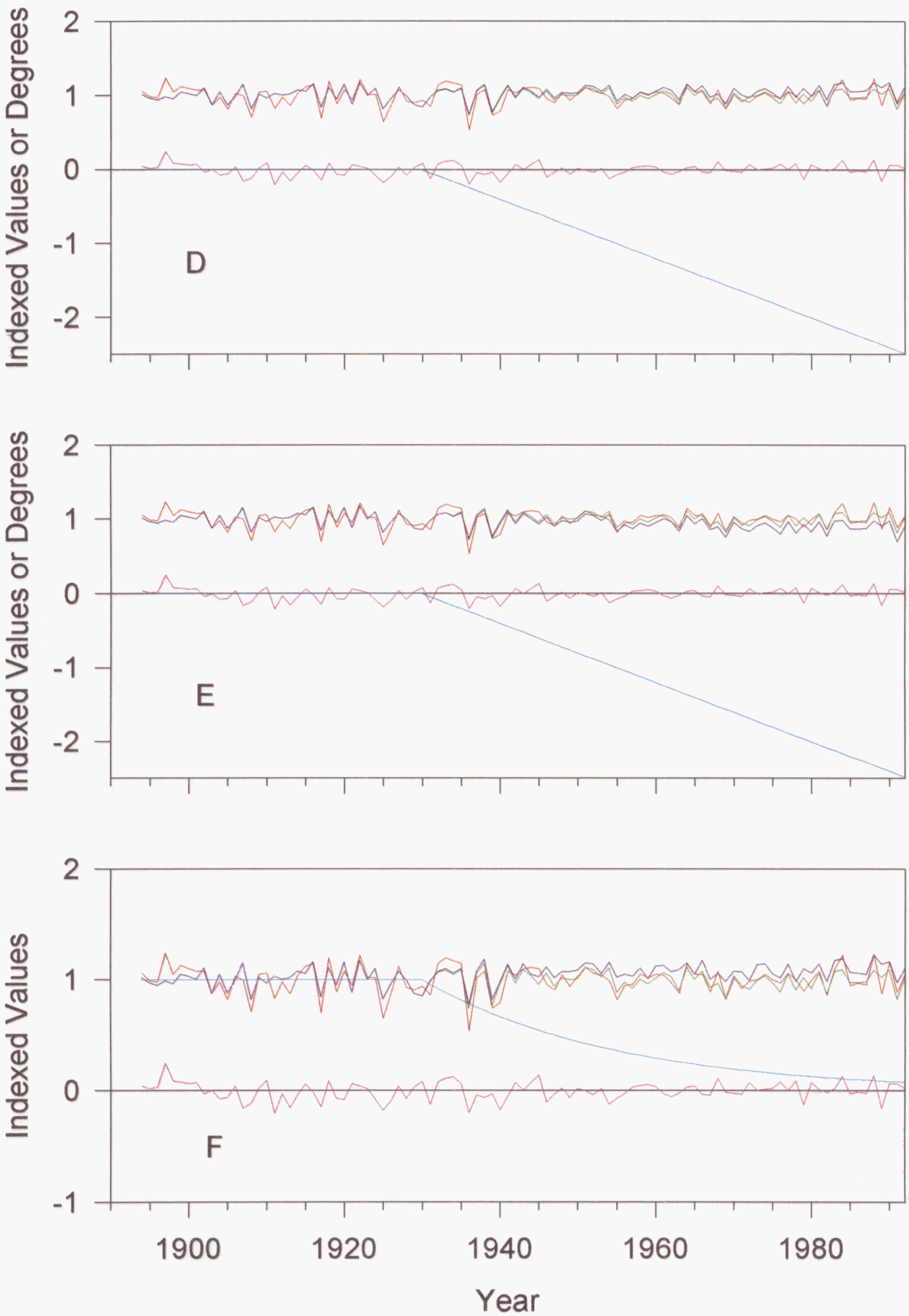


Figure 5.7 (continued) **D.** Calculated effect of a 0.04°C decrease per year in December-February temperature begining in 1931 on the ring-width index using the response function in B. **E.** Same as D except for a decrease in September-November temperature. **F.** Same as E except for March-May precipitation of 4% decrease per year.
—— Actual indices —— Estimated indices —— Estimates with climate change
—— Actual minus estimates —— Climatic change.

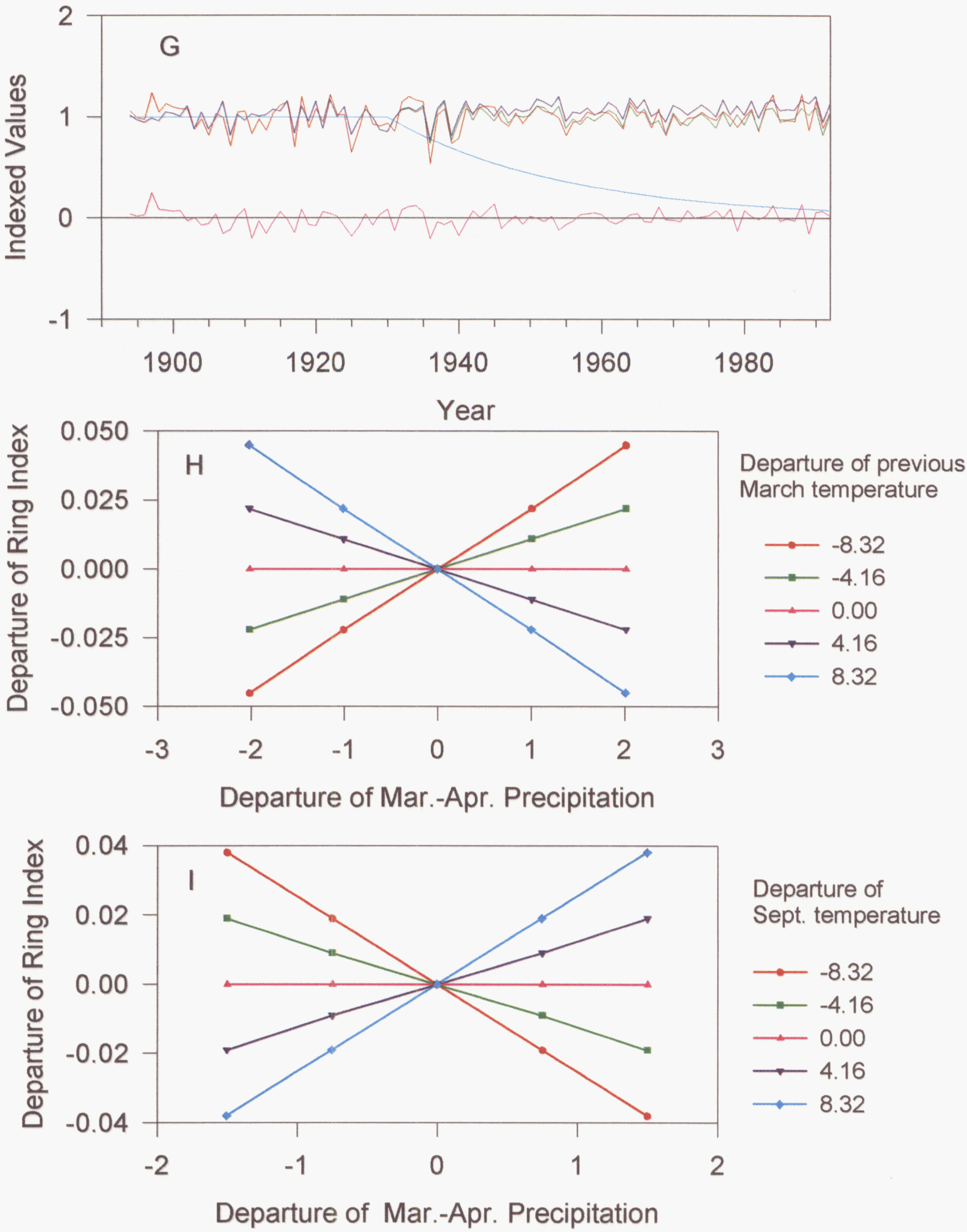


Figure 5.7 (continued) **G**. Same as F except for a decrease in June-August precipitation. **H**. A significant interaction between March-April precipitation and March temperature, portrayed by solving for the effect of March temperature on growth while holding March-April precipitation at seven levels standard deviation of the variable. **I.** Same as H except for an interaction between March-April precipitation (holding at five levels) and September temperature.

Correlation (Figure 5.6a), response function analysis (Figure 5.6b) and multiple regression analysis (Figure 5.6c) demonstrate that temperature is inversely related to growth in February to April of the prior growth season. The correlation or response coefficients for precipitation are negative in all the prior growth and early growth season and significant in March, April and August (response function) but are positive from January to March. This was confirmed by the results of the electric dendroband study (Appendix 1). This suggests that high precipitation in winter and in the early spring growth season can limit ring-width growth. The multiple regression analysis includes significant positive temperature coefficients for September and the current February and negatively significant for March and December. The inverse effect of prior February and March temperature may be related to the colinearity between predictor variables of growth and the ARMA modelling, which may have over-corrected for autocorrelation by not taking into account the nonrandom effects of prior summer climate on growth.

There are ten response function coefficients which differed significantly from zero compared to six for the correlation analysis and eight for the multiple regression analysis. The dominant negative effect of both prior summer and autumn temperature are evident.

The coefficients from either the multiple regression or the response function can be applied to the effects of climate change on ring-width growth. Response function coefficients were used to generate the plots in Figure 5.6d-f. In these plots, the red line portrays the actual ring-width indices, the green line the response function estimates, and the pink line the residuals from the response functions. The blue line shows the solution of the response function equation when the hypothesised climatic change amounts are incorporated into the climatic values used to generate the original regression estimates. The blue line completely obscures the green line up to 1931, because no climatic change is simulated and no differences exist between the two estimates. After 1931, the blue and green line diverge indicating the degree to which a change in precipitation or temperature affects ring-width. The cyan line shows the change in temperature or precipitation that was used in the simulation.

In Figure 5.6d-g, the change was applied to December-February temperature, September-November temperature, March-May precipitation and June-August precipitation. The declining summer (December-February) temperature contributed to higher growth (i. e. wider ring) but the September-November temperature related to lower ring growth. Declining precipitation in autumn and winter contributed to greater tree-ring growth.

PRECON was used to check for nonlinear effects and interactions by generating squared and cross-product terms for all significant coefficients in the multiple regression showed in Figure 5.6h-i. When March and April precipitation was high, high previous March temperature contributed to lower ring-width but high September temperature contributed to higher ring-width growth; When March and April precipitation was low, high previous March temperature had a positive effect on ring-width but high September temperature had a negative or reverse effect on ring-width.

5.4.3 Group B chronologies and averaged regional climate data

There are nine significant coefficients in the response function analysis between the combined Group B chronology (5 chronologies) and average meteorological data series from C94001, C95251 and E95681 (Figure 5.7b). February temperature is positively related with the current ring-width but inversely correlated with the next ring-width. August and October precipitation is negatively related with ring-width but current March is positively related with ring-width. There is one more negative significant temperature coefficient (April) in correlation and multiple regression. The fractional variance reduced, ranged from 0.432 for the multiple regression to 0.627 for the response function (Table 5.12). Tree growth increased when it was simulated with a decline in winter (June-August) and spring (September-November) precipitation (Figure 5.7f,g). When a decrease in summer and spring temperature was modelled, there was a positive or negative simulated change in growth (Figure 5.7d,e). Examination of interactions for variables significant in Figure 5.7h showed that when August precipitation was high, high previous February temperature were related with narrow rings; but when August precipitation was low, high previous February temperature was related with wide rings.

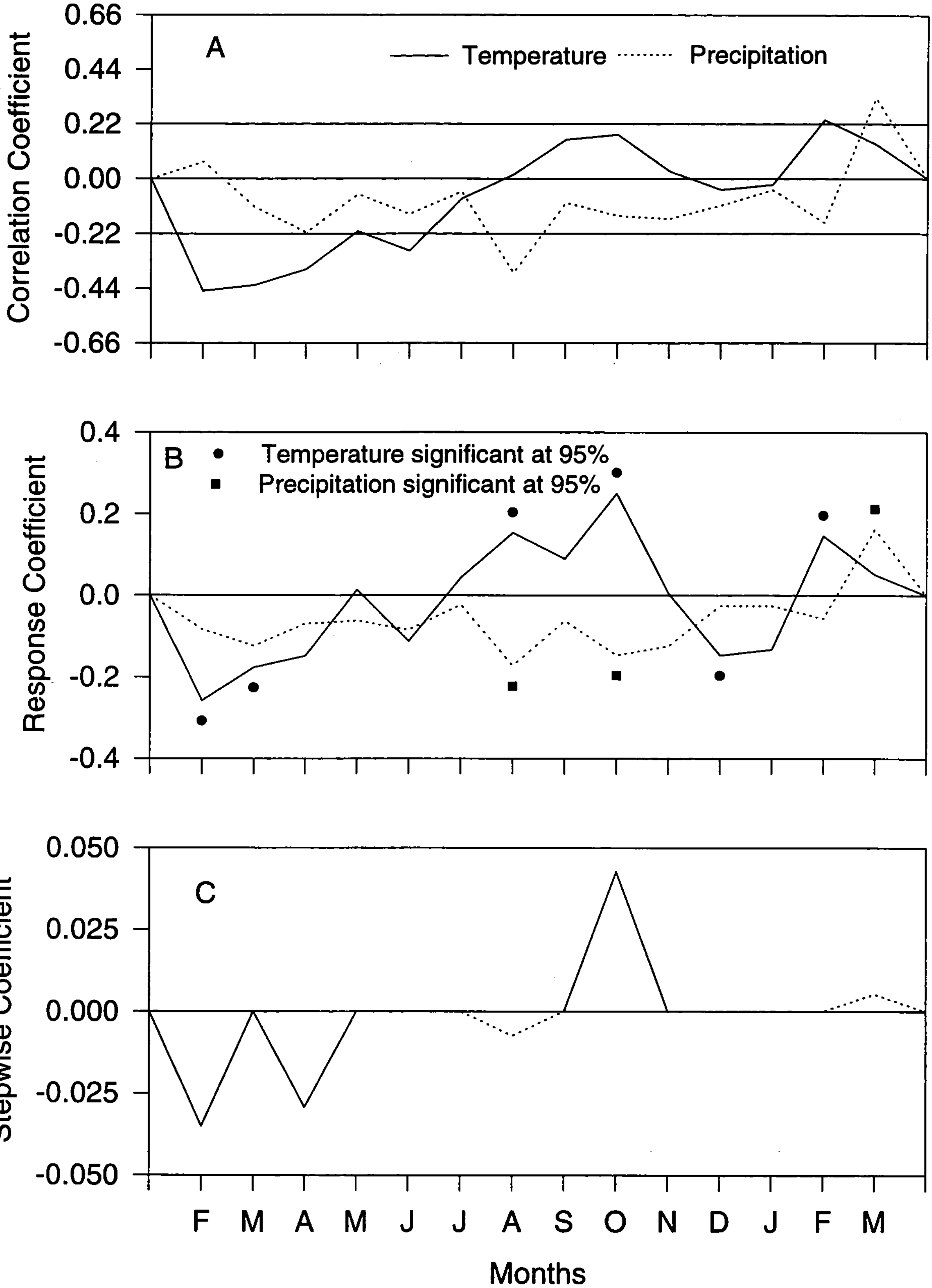


Figure 5.8 Analysis of Group B chronology with averaged regional meterological data series. **A.** Simple correlation function. The line at 0.22 indicates significant at 95%. **B.** Bootstrap response function. **C.** Stepwise multiple regression. Coefficient value selected when F > 3.5.

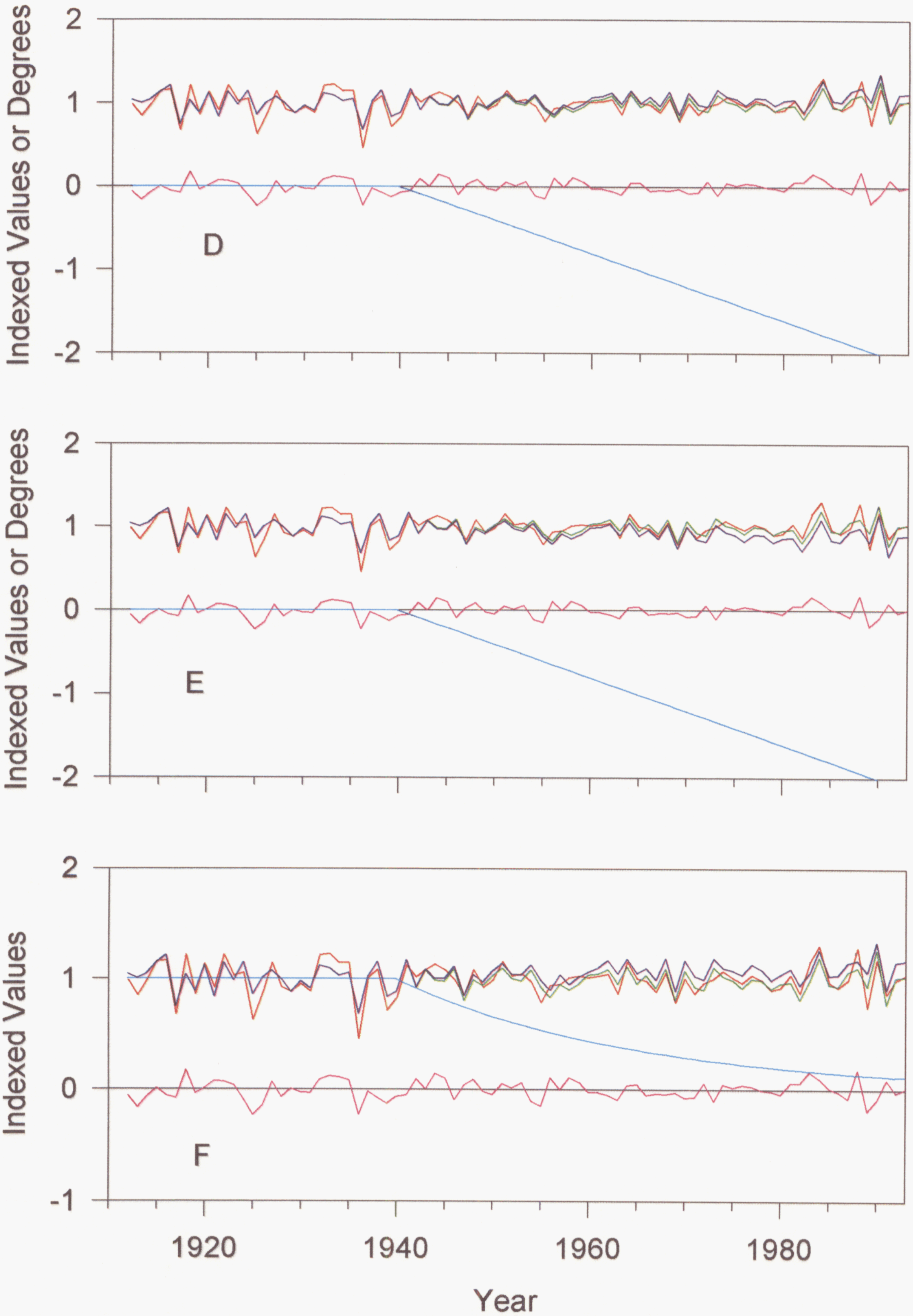
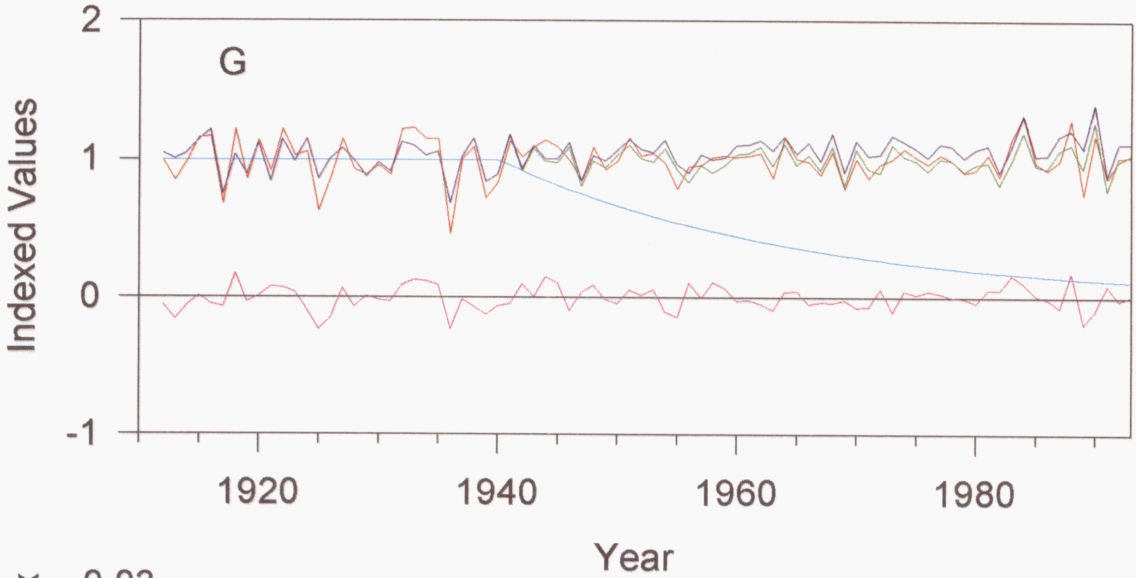


Figure 5.8 (continued) **D.** Calculated effect of a 0.04°C decrease per year in December-February temperature begining in 1941 on the ring-width index using the response function in B. **E.** Same as D except for a decrease in September-November temperature. **F.** Same as D except for a decrease in June-August precipitation of 4% per year. ——— Actual indices ——— Estimated indices ——— Actual minus estimates ——— Estimates with climate change ——— Climatic change.



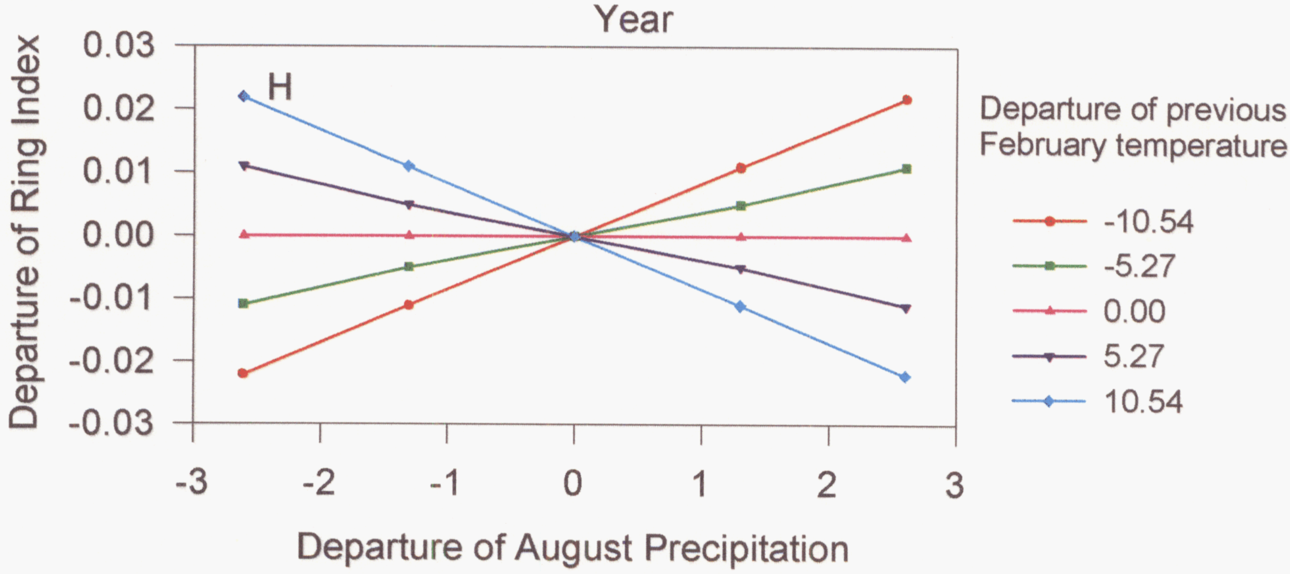


Figure 5.8 (continued) **G**. Same as F except for a decrease in Sept.-Nov. precipitation. **H**. A significant interaction between August precipitation and February temperature, portrayed by solving for the effect of February temperature on growth while holding August precipitation at seven levels of standard deviation of the variable.

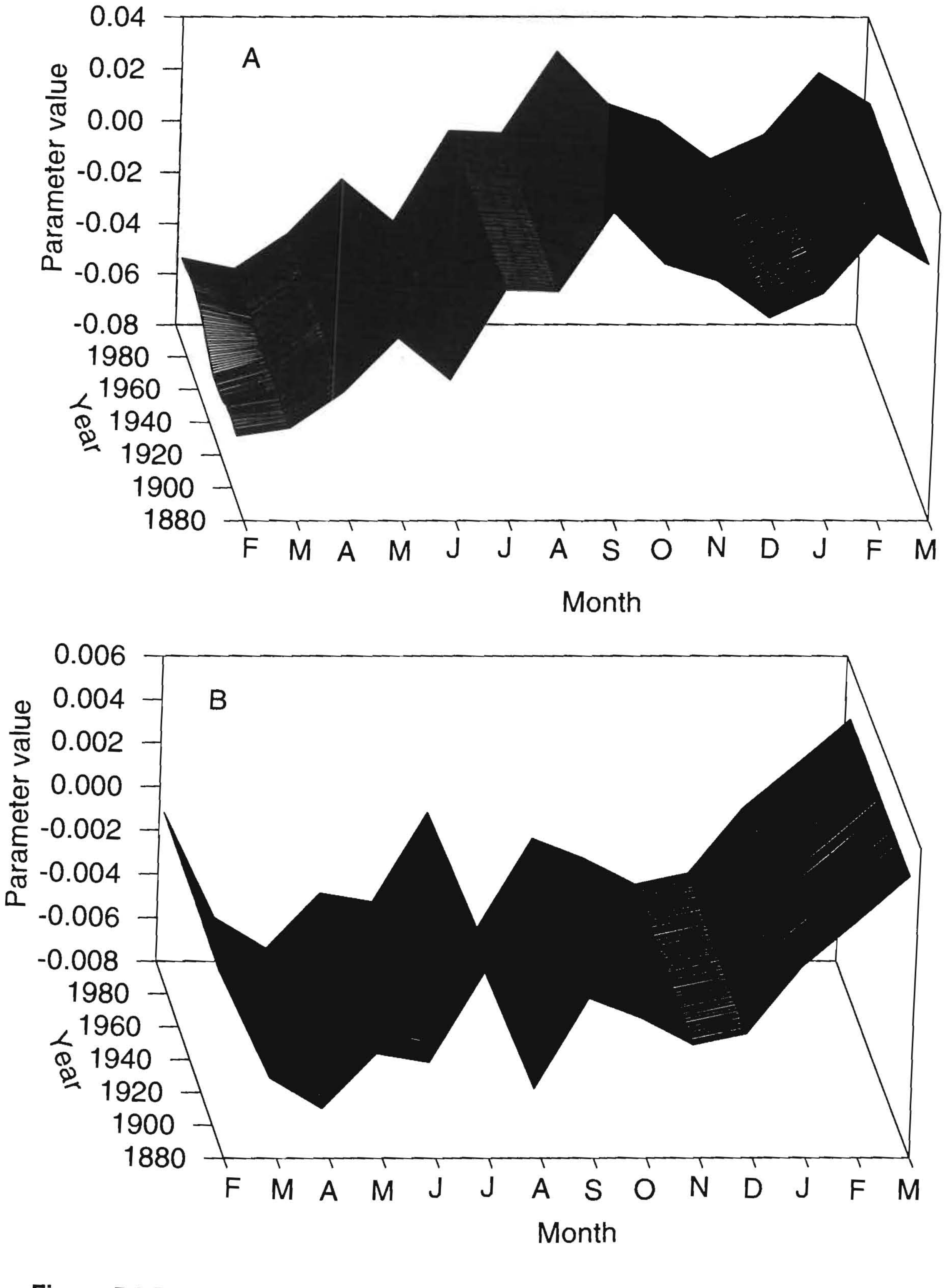


Figure 5.9 Three-dimensional representation of the stochastic response function of GROUP A chronology with NZ average climate data. A. Temperature. B. Precipitation.

5.5 Kalman filter technique

One potential problem with the discussion above on response functions is the assumption of constant coefficients (i.e. the relationships between climatic and biological process did not change with time). There are two problems with the assumption: firstly, threshold phenomena can never be detected; secondly, it is to be expected that the sensitivity of trees to weather variations changes over time. This may be caused by natural processes (e.g., aging of trees, climatic changes) as well as by anthropogenic influences (e.g. increasing levels of air pollution). Puckett (1982), Phipps (1983), McClenahen & Dochinger (1985) and Peterson *et al.* (1987) tried to overcome this problem by splitting up the available time series into two or three parts and estimating response functions for the separate time intervals. In order to solve this problem better, Van Deusen (1987) and Visser & Molenaar (1986, 1988) introduced the Kalman filter (Kalman, 1960) into dendroclimatology.

The Kalman filter in PRECON (Cook, 1994) was used to analyse the relationship between the Group A chronology and the NZ average climate data series (Figure 5.8). The result showed that *Libocedrus bidwillii* responded to most of the climate variables constantly over the last 100 years in New Zealand. The only exception was the previous February temperature where the tree response was variable over time. However, the variation was very small (below 0.01) and all coefficients were negative. This may be because the environment of New Zealand (especially the sites we sampled) was not disturbed as much as those in Europe and North America. It can be concluded that the general response function discussed above did reflect the relationship between tree growth and climate through time.

5.6 Chapter conclusions

1. The best climate parameters to use were average monthly temperature and average monthly precipitation.

2. February to March was the optimal 14 month span of those spans tested.

3. There was no significant relationship between separation distance (meteorological station and chronology) and the variance reduced by the response function analysis.

4. Based on the verification results and the binomial distribution test, 27 pairs of response functions were significant out of 69 possible response functions. In general the response functions showed a negative relationship between temperature for the prior growth months February, March and current December, while there was a positive response to temperature in September and February. There were three significant negative coefficients (previous March, April and August) and one positive (current February) for precipitation.

5. PCA (Principal Component Analysis) showed that the 27 significant response functions could be grouped into four: A. national wide representative group; B. central North Island group; C. east coast group in the North Island; D. west coast group in the South Island.

6. The using of residual chronologies without prior growth and 14 months time span (February - March) was confirmed by the results of more significant coefficients in the residual chronology, no significant lag effect in the residual chronology and no significant coefficients in previous January and after current March in residual chronology.

7. The response functions for the new climate data-base and combined chronology of the four groups showed that three of the four response functions were significant when independently verified (but one group was near the margin of significance). Temperature had a similar response pattern in different groups but the rainfall response was more variable.

8. The result of using the Kalman filter showed that *Libocedrus bidwillii* responded to most of the climate variables constantly over the last 100 years in New Zealand. The general response function reflected well the relationship between tree growth and climate change.

9. The potential for climate reconstruction offered by the data has now been confirmed. The reconstruction in the next chapter is based on two groups only (A and B), representing national and regional coverages.

CHAPTER SIX

CLIMATE RECONSTRUCTIONS

6.1 Introduction

The principal aim of this thesis was to reconstruct New Zealand's past climate from tree-rings. In this chapter this was finally achieved.

The chapter starts by describing the selection of a bootstrap transfer function model to reconstruct past temperatures and rainfall using the response function results produced in chapter 5. The first section discusses the transfer function itself by comparing the general method with that of the bootstrap method. All the possible variables were tried and the best one was selected for further reconstruction.

The second part of the chapter discusses the actual and reconstructed climate series. Specific aspects were discussed in terms of: (1) individual warm years, warm periods, cool years and cool periods; (2) comparison with other reconstructions from tree-ring data; (3) comparison with other sources of past climate information such as glacial, speleothem isotope palaeotemperatures and lake levels.

6.2 Transfer function

6.2.1 General methods

The rationale for the use of transfer function techniques has been discussed by Fritts (1976), Fritts *et al.* (1971, 1979), Lofgren & Hunt (1982), Briffa *et al.* (1983, 1986), Briffa (1984) and Till & Guiot (1990). In transfer function analysis, data from a network of tree-ring chronologies are regressed against recent climate data to calibrate the transfer function. This transfer function is then tested on independent data ('verification') and finally applied to the period prior to instrumental records as an estimate of past climate.

The basic model used to compute a transfer function is multiple regression. The first step in the multiple regression technique is to transform the tree-ring chronology time series into their principal components. The PC rejection criterion normally used is the PVP method devised by Guiot (1981) (in which the components retained are those for which the cumulative product of eigenvalues exceeds 1). The next stage is to use the reduced set of PCs as candidate predictors in a multiple regression equation.

Tree-ring series are often strongly autocorrelated. Although these patterns were removed using autoregressive filters resulting in a prewhitened series, the inclusion of previous growth (i-1) was still considered a prudent step. Thus, for each chronology, values for year i-1, i and i+1 were used as predictors in the regression

$$C_i = f(W_{i-1}, W_i, W_{i+1}) \qquad (6.1)$$

analysis (Fritts, 1976). Consequently the following model was investigated:
Where, C_i is climate in year i, W are the ring width data.

Because of the empirical nature of the climate tree-ring links, the results cannot be guaranteed to perform well over an independent period. The verification of regression models using independent data is one of the strengths of dendroclimatology. A number of verification tests are commonly used (Fritts, 1976; Fritts *et al.* 1981; Gordon *et al.* 1982). In all of these tests the regression equation established over the calibration period is used to calculate the climate parameter over an independent period for which actual climate data exists. The estimated values are then compared with actual values during this period. The most obvious method of comparison is to calculate the correlation coefficient. The correlation coefficient is *expected* to be less over the verification period; but if the model is good, the correlation should be similar and must preserve its statistical significance (Briffa *et al.* 1983). A more searching verification test is provided by the Reduction of Error statistic (RE) (Lorenz, 1956; Fritts, 1976). This parameter effectively compares the estimated values with estimates made simply by assuming all values in the verification period to be the mean values for the calibration period. If the RE is calculated for the calibration period, its value is simply the square of the correlation coefficient. Over the verification period, RE can range from $-\infty$ to 1. The Reduction of Error (RE) equals zero in the case where the regression provides no useful information. A value of RE > 0, therefore, demonstrates the usefulness of the regression estimate.

6.2.2 Bootstrap method

Bootstrapping is a recent technique (Efron, 1979; Till & Guiot, 1990) for estimating statistics of an unknown population distribution by Monte Carlo simulations. The idea is to resample the original observations in a suitable way so as to construct pseudo-data sets on which the estimates are made. A regression is computed on this pseudo-data set. The entire process is repeated an arbitrary number of 50 times (this number has been tested by Guiot, refer to Fritts *et al.*, 1990; Fritts & Dean, 1992). The fifty reconstructions of the predicants are summarised in a median series comprised between a lower-limit series (5th percentile) and an upper-limit series (95th percentile). This confidence interval gives an idea of the effective confidence which may be placed in the results. Similar confidence intervals are also computed on the regression coefficients.

For each pseudo-data set, an independent verification is done on the observations which are not included in the regression. The goodness of fit is computed in the following steps: (1) the reconstruction is compared to the actual climatic series both on the retained observation set and on the independent set; verification statistics are also calculated 50 times. (2) the mean and standard deviations of the verification statistics are obtained dependently on the calibration and independently on the observations not included in the calibration. (3) the final reconstruction is the median of the 50 replicated reconstructions and a 90% confidence interval is given by the 5th and 95th percentiles.

The bootstrap method is not, by itself, an improvement of the calibration methods, but rather an improvement in interpretation of the verification statistics. This verification may be done without making assumptions regarding the distribution of the residuals and without eliminating data. Indeed, the data which are lost in one given pseudo-data set (and kept for the independent verification) are recovered in the other ones. This advantage is particularly important when climatic series are short. Another advantage is that the reliability of the reconstructions can be assessed by confidence intervals (Till & Guiot, 1990).

6.3 Methods

The Windows based program PPPBASE, developed by J. Guiot (1995), was used. The reconstruction was started by effectively performing a response function analysis but with tree-ring indices rather than monthly climatic data as orthogonalised regressors (*i.e.* calibration). Group A (with 11 chronologies), the three longest chronologies from Group A (TOB, TOC, HIT, in order to extend back 500 years) and Group B (with 5 chronologies) were chosen. These are based on the results of Chapter 5. All the chronologies included year i, year i-1 and year i+1. PCA analysis was applied to all the chronology groups. Guiot's "PVP" criteria (Guiot, 1987) was used for curtailing the initial number of principal components once the cumulative product of the eigenvalues failed to exceed one.

The climate data, by which the chronologies were calibrated, consisted of several values for each year. These values are the mean or total of a preselected set of months (*e.g.* summer, autumn) of a single climate variable (temperature or precipitation). The selection of the months was based on the response function results (Chapter 5). Bootstrap transfer function is used to analysis all the variables, the final decision was made based on the independent verification results.

Comparisons were made between the general method and the bootstrap method, and the observed and reconstructed climate data. The final reconstructions were confirmed on the basis of verification results and spectral analyses. Finally, the reconstructed climate data series were discussed in detail.

6.4 Results

The retained PCs of tree-ring data constituted a set of candidate predictors which were used in a multiple regression against the climate variables. The number of retained PCs are shown in Table 6.1.

Table 6.1 Variance associated with principal components in PCA analysis with PVP cut-off

	Eigenvalue	% Variance	Cumulative
Group A chronologies			
PC1	0.303	22.75	22.75
PC2	0.236	17.73	40.48
PC3	0.208	15.61	56.09
PC4	0.152	11.41	67.50
PC5	0.069	5.19	72.69
PC6	0.062	4.64	77.33
PC7	0.053	3.97	81.30
PC8	0.040	3.04	84.34
PC9	0.039	2.90	87.24
PC10	0.035	2.67	89.91
PC11	0.027	2.05	91.96
PC12	0.016	1.22	93.18
PC13	0.016	1.20	94.38
The three longest chronologies of Group A			
PC1	0.060	27.89	27.89
PC2	0.054	25.22	53.11
PC3	0.051	23.97	77.08
PC4	0.010	4.62	81.70
PC5	0.009	4.37	86.07
PC6	0.008	3.96	90.03
Group B chronologies			
PC1	0.090	25.53	25.53
PC2	0.082	23.24	48.77
PC3	0.072	20.43	69.20
PC4	0.020	5.65	74.85
PC5	0.019	5.27	80.12
PC6	0.018	5.21	85.33
PC7	0.009	2.45	87.78
PC8	0.007	2.03	89.81
PC9	0.007	1.93	91.74

The results of the transfer function models are presented in Table 6.2. Comparison of the models was made among Group A, the three longest chronologies in Group A and Group B.

Table 6.2 Climate reconstruction models using the bootstrap method (50 replications). All combinations include growth in year i, i-1 and i+1.

Model[1]	Variables	Months	Calibration[2]	Verification[2,3]
Ia		Feb.-Mar.	.653±.035	.405±.094*
b	Temperature	Sept.	.488±.067	.124±.096
c		Sep.-Nov.	.491±.054	.082±.117
d	(135 years)	Dec.-Jan.	.471±.064	.072±.114
e		Dec.-Feb.	.527±.056	.175±.116
f		Feb.	.569±.044	.276±.109*
g		Mar.-Apr.	.597±.058	.244±.104*
h	Precipitation	Mar.-May.	.595±.064	.256±.107*
i		Jun.-Aug.	.509±.059	.061±.114
j	(100 years)	Aug.	.486±.053	.012±.104
k		Dec.-Feb.	.434±.069	-.123±.139
l		Feb.	.484±.074	-.033±.117
IIa		Feb.-Mar.	.429±.059	.313±.102*
b	Temperature	Sept.	.326±.054	.189±.099
c		Sep.-Nov.	.237±.053	.039±.098
d	(138 years)	Dec.-Jan.	.226±.057	-.004±.109
e		Dec.-Feb.	.217±.051	-.011±.101
f		Feb.	.271±.054	.058±.110
g		Mar.-Apr.	.507±.052	.322±.110*
h	Precipitation	Mar.-May	.435±.062	.212±.116
i		Jun.-Aug.	.285±.064	-.016±.115
j	(103 years)	Aug.	.350±.051	.132±.119
k		Dec.-Feb.	.235±.065	-.106±.108
l		Feb.	.287±.065	-.120±.116
III a		Feb.-Mar.	.620±.052	.385±.145*
b		Aug.	.364±.066	-.070±.144
c	Temperature	Oct.	.434±.084	.044±.157
d		Aug.-Oct.	.416±.076	-.026±.174
e	(77 years)	Dec.	.401±.073	-.088±.166
f		Dec.-Feb.	.435±.064	-.017±.169
g		Feb.	.535±.071	.270±.149
h	Precipitation	Aug.	.360±.053	.092±.125
i		Aug.-Oct.	.320±.049	-.002±.117
j	(124 years)	Oct.	.339±.060	.044±.136
k		Mar.	.334±.056	.034±.127

Note:
1. Model I is based on Group A chronologies and the New Zealand average meteorological data series. Model II is based on the three longest chronologies in Group A and the NZ average climate data series. Model III is based on Group B chronologies and regional climate data series.
2. The value is the mean of multiple correlation coefficients and their standard deviations.
3. * indicates the independent verifications are significant at 95% level.

The results of the general transfer function method applied to the four significant variables has been given in Table 6.3. Further comparisons of the bootstrap method and the general method for Group A are shown in Figures 6.1 and 6.2.

Table 6.3 The results of the general transfer function for Group A and the three longest chronologies

		Period	Mean		S.D.		Corr.	Sign	R.E.
			Obs.	Rec.	Obs.	Rec.		Product	
G	Calib.	1853-1920	15.60	15.60	.824	.488	.639	16*	.406
R	Verif.	1921-1987	16.14	15.55	.876	.493	.426	26*	.065
A	Calib.	1921-1987	16.14	16.13	.876	.629	.797	20*	.629
T	Verif.	1853-1920	15.60	16.07	.824	.579	.347	22*	.076
G	Calib.	1888-1937	233.84	233.81	80.66	49.99	.693	16*	.475
R	Verif.	1938-1987	240.22	236.35	86.33	50.57	.0967	24	-.225
A	Calib.	1938-1987	240.22	240.45	86.33	53.14	.718	13*	.505
P	Verif.	1888-1937	233.84	229.05	80.66	66.43	.302	16*	-.177
T	Calib.	1853-1920	15.60	15.61	.824	.311	.388	27*	.150
H	Verif.	1921-1990	16.15	15.62	.876	.302	.316	34	.089
R	Calib.	1921-1990	16.15	16.14	.876	.465	.525	25*	.276
T	Verif.	1853-1920	15.60	16.12	.824	.498	.271	24*	.007
T	Calib.	1888-1940	232.21	232.59	83.87	46.86	.562	14*	.316
H	Verif.	1941-1990	243.36	233.22	82.58	48.63	.249	21	-.049
R	Calib.	1941-1990	243.36	243.32	82.58	42.65	.520	18*	.271
P	Verif.	1888-1940	237.21	246.26	83.87	80.11	.345	21	-.260

Note:
* indicates significant at 95% level.
S.D. : Standard Deviation; R.E.: Reduction of Error; Obs.: Observed climate data; Rec.: Reconstructed climate data; GRAT: Temperature reconstructed from Group A chronology; GRAP: Precipitation reconstructed from Group A chronology; THRT: Temperature reconstructed from the three longest chronologies; THRP: Precipitation reconstructed from the three longest chronologies.

The actual and reconstructed climate data were plotted in Figure 6.3 to check if extreme data were consistently under or over estimated. In order to check if cyclic patterns in the climate data were being modelled the spectral properties of the observed and the reconstructed series were plotted (Figure 6.4) and the similarities shown in a coherency diagram (Figure 6.5).

The comparison between observed and reconstructed climate data for 10-year-average is presented in Figures 6.6 and 6.7. The frequencies per decade of climate conditions greater than one standard deviation above or below normal are shown in

Figure 6.8 and 6.9. Finally, the reconstructed February-March temperature, March-April precipitation and their 90% confidence interval are shown in Figures 6.10 and 6.11.

6.5 Discussion

6.5.1 PCA analysis

From Table 6.1, it can be seen that, PVP selection results in more than 90% of the variance of the original predictor set being retained. The number of variables in all three cases is reduced by about a half to a third.

6.5.2 Selection of variables for climate reconstruction

A judgement was made on the best variables to use for climate reconstruction based on the independent verification. If the correlation coefficient of the independent verification is two times larger than its standard deviation, the model is significant at the 95% level (Guiot, 1991). Only seven models were significant in the independent verification data. The previous February-March temperature was significant in all three groups (Table 6.2, model Ia, IIa and IIIa). March-April precipitation was significant in Group A and the three longest chronologies (Table 6.2, model Ig and IIg). Only one temperature variable was significant in Group B, which also reconstructed the NZ average temperature in the same manner of Group A. Therefore Group B will not be discussed further.

6.5.3 Comparison of general method and bootstrap method

Table 6.3 showed that the pair of models based on temperatures gave better results than those based on precipitation since they were successfully verified in both independent verification periods (positive RE). However, there was a large difference in the correlation and RE value depending on which period was used for calibration. The RE of the verification is negative in both precipitation reconstructions. The plots of the actual and reconstructed climate data against time (Figure 6.1 and Figure 6.2)

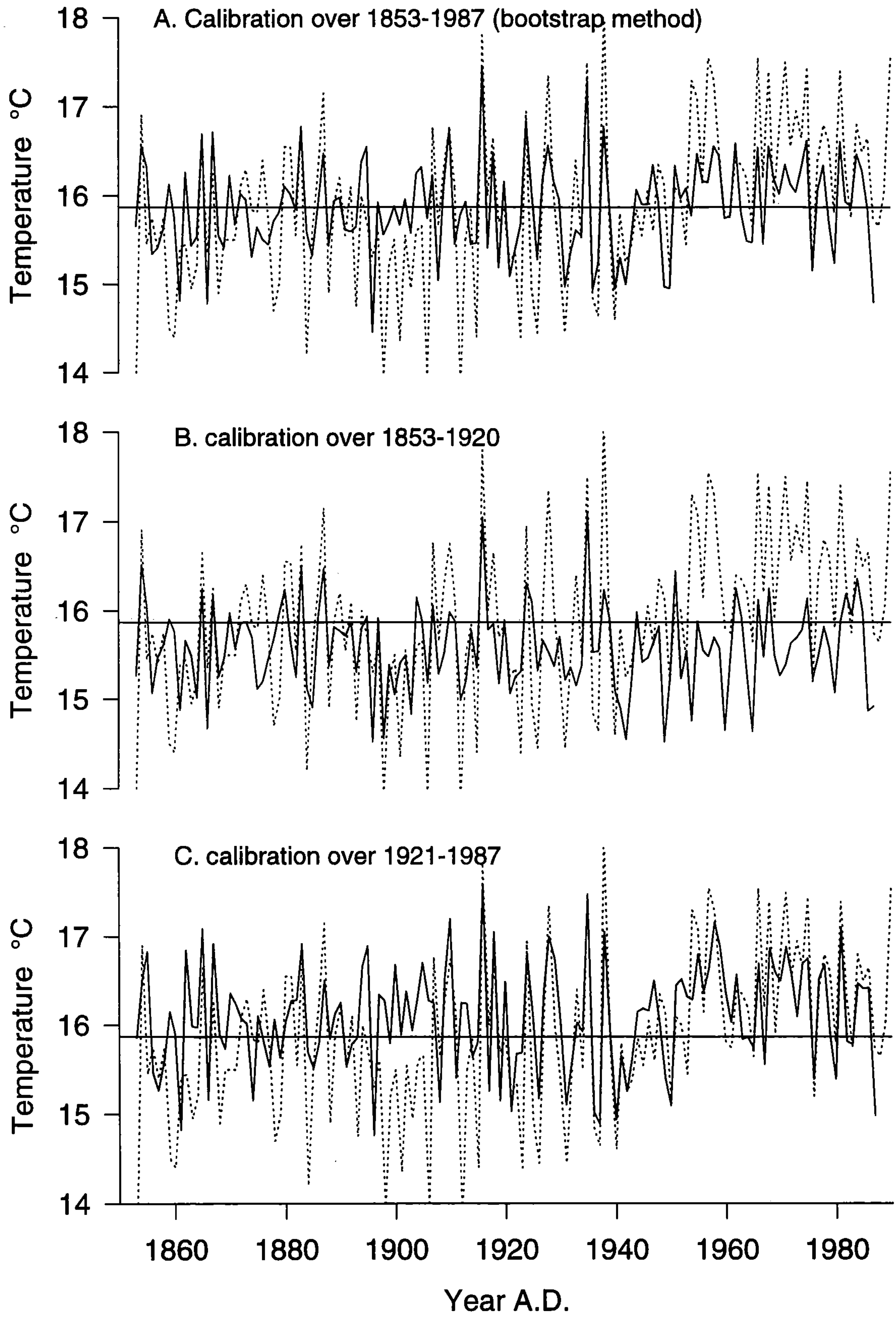


Figure 6.1 Comparison of observed and reconstructed February- March temperature from Group A chronologies. ——— Reconstructed ········ Observed

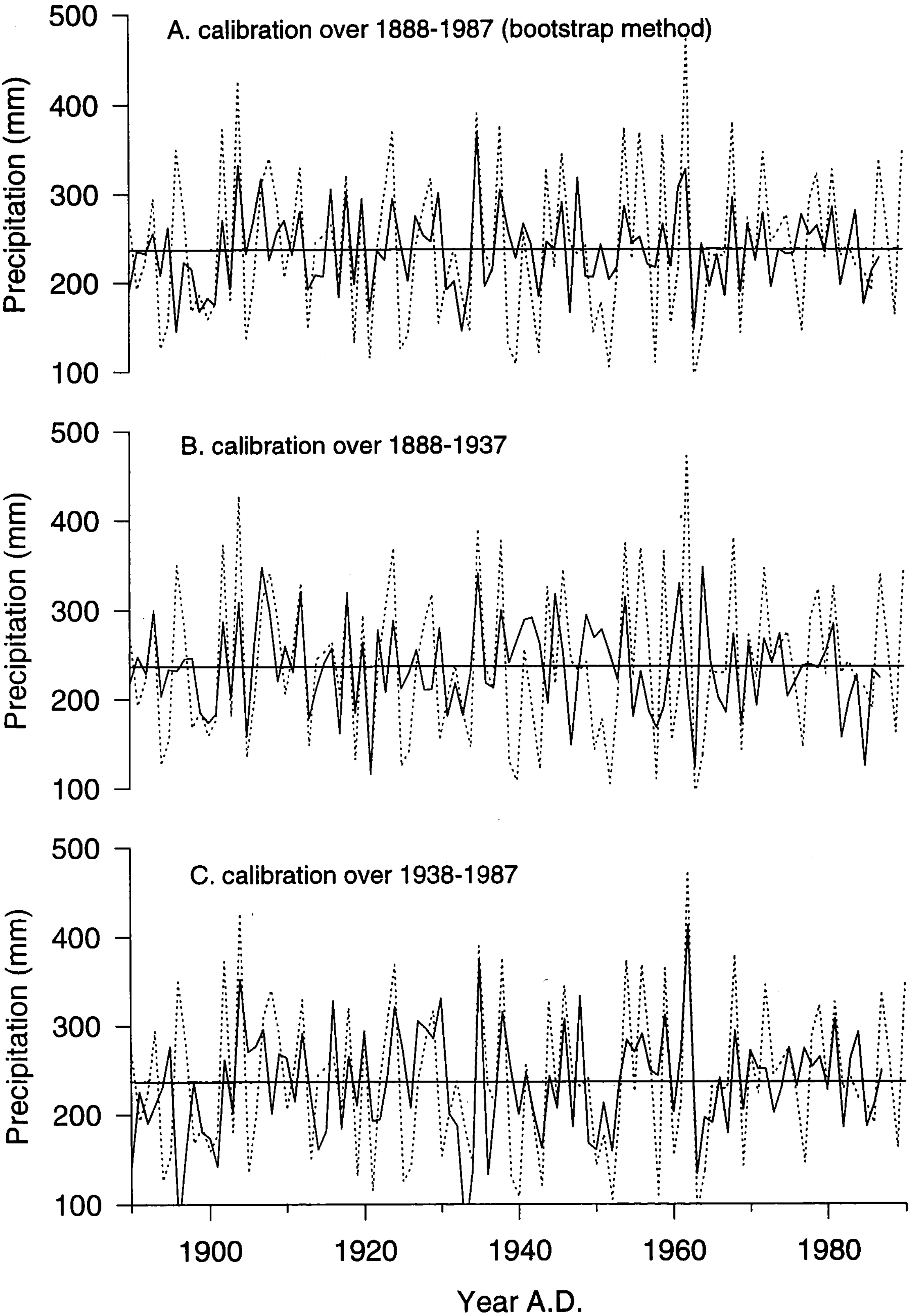


Figure 6.2 Comparison of observed and reconstructed March-April precipitation from Group A chronologies. ——— Reconstructed ········ Observed

showed the general tendency for the reconstructed values to have a smaller amplitude than the observed values, a predictable feature since only a percentage of the observed variation has been modelled. The reconstructed climates can, therefore, be considered to be conservative estimates of actual climate.

The mean observed Feb.-Mar. temperature for the 1853-1987 period was 15.87±0.889°C. There was a higher temperature (16.14±0.876°C) in the period 1921-1987 compared with the period 1853-1920 (15.60±0.824°C). The same trend occurred in the Apr.-May mean rainfall data with 233.84±80.66mm in the period 1888-1937 and 240.22±86.33mm in the period 1938-1987. As expected, the difference and the variation was less in the reconstructed series and strongly dependent on which period was used in calibration. The reconstructed temperature mean over the 1853-1920 calibration was 15.60±0.488°C. Over the 1921-1987 calibration it was 16.13±0.629°C and the mean temperature from bootstrap method was 15.86±0.535°C. The reconstructed precipitation mean over the 1888-1937 calibration is 233.81±49.99mm, over the 1938-1987 calibration was 240.45±53.14mm and the mean precipitation from the bootstrap method was 238.01±36.43mm. Figures 6.1 and 6.2 showed that the early period calibration led to an under-estimation of the later period (Figures 6.1B & 6.2B) and the late period calibration led to over-estimation of the early period (Figures 6.1C & 6.2C). Only the bootstrap method solved this problem. Overall, from the figures, it was obvious that the bootstrap method was better than the general method because it was calibrated over a longer time period and still could be independently verified.

6.5.4 The quality of reconstructed climate data using the bootstrap method

The plot of the actual against reconstructed climate (Figure 6.3A, C) showed how the model approximated the ideal regression line and indicates the poorly reconstructed years (i.e. outliers). In the temperature reconstruction from Group A, 13 of the 20 hottest observed years (above standard deviation) were also among the 21 hottest reconstructions. Only 5 of the 22 coldest observed years are found in the 18 coldest

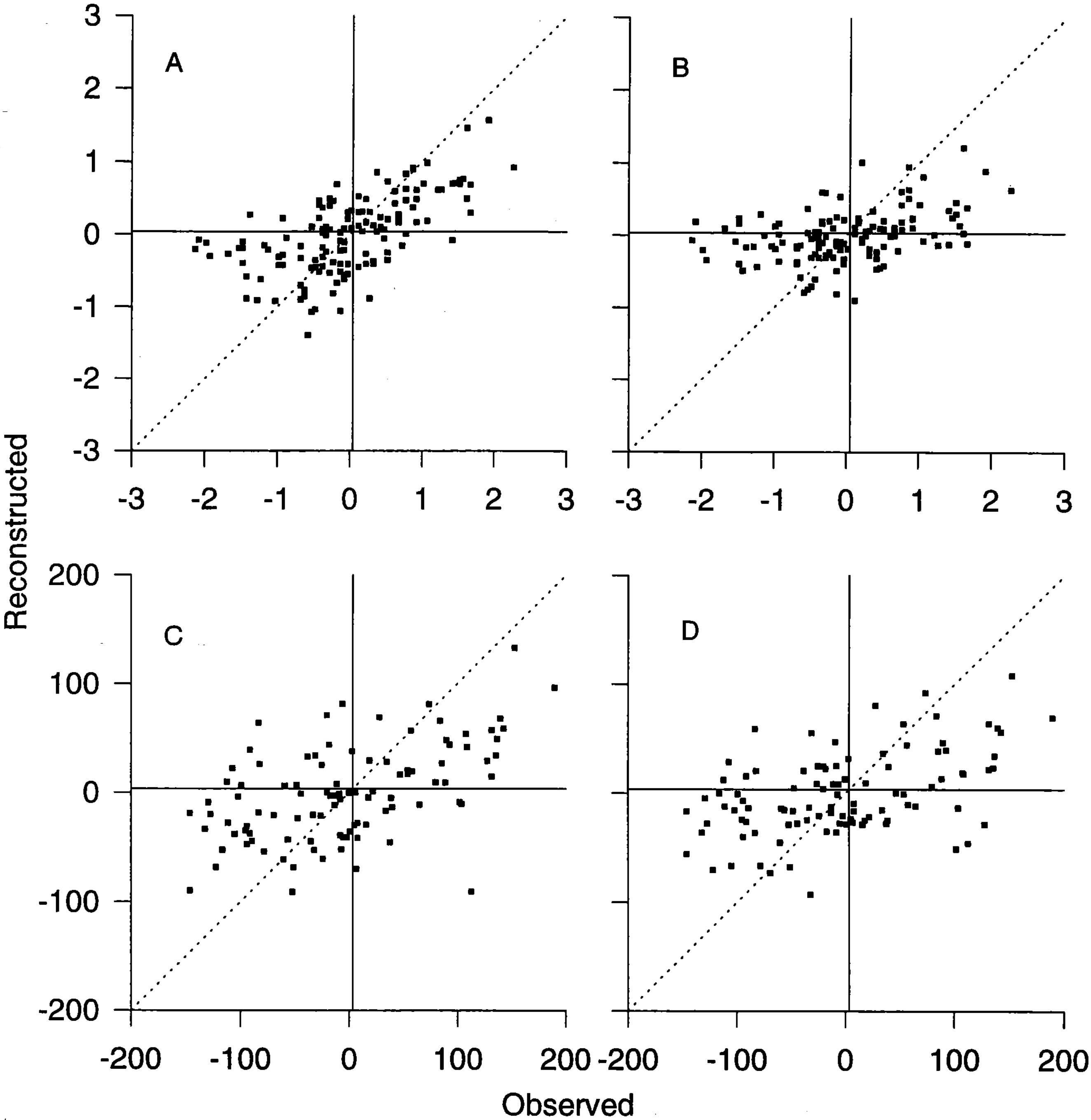


Figure 6.3 Comparison of the observed against reconstructed climate data. A & B are temperature, C & D are precipitation. A & C are reconstructed from Group A. B & D are reconstructed from the three longest chronologies.

reconstructions. Temperature reconstructed from the three longest chronologies showed that 7 of the 20 hottest observed years were among the 16 hottest reconstructions. However, only 4 of the 22 coldest observed years were found in the 18 coldest reconstructions (refer to Appendices 3 & 4). Both groups generally were able to reconstruct hot years but seemed less able to reconstruct cold years. Hot years were not well reconstructed during the period 1950-1987. There were 13 hot years in the observed data from 1950-1987, 8 in the reconstructions from Group A, but only 2 in the reconstructed temperature data from three longest chronologies. It is obvious that the temperature reconstruction from Group A is better than that of the three longest chronologies even though both transfer functions were verified. Further discussion of the reconstructions from the three longest chronologies was still considered worthwhile because they are the only data series that extends back 500 years in New Zealand.

The precipitation reconstruction from Group A showed that 8 of the 22 driest observed years were among the 24 driest reconstructions and 12 of the 20 wettest observed years were among the 22 wettest reconstructions. In the reconstructions from the three longest chronologies, there were only 5 of the 22 driest observed years among the 10 driest reconstructions and 8 of the 20 wettest years were found in the 14 wettest reconstructions (refer to Appendices 3 & 4). Group A reconstructed more extreme years (46) than did the three longest chronologies (24). However, the reconstruction from the three longest chronologies had a higher match ratio with observed data (13/24) than that of Group A (20/46).

Figure 6.4 showed the variance spectra for both the observed and reconstructed climate data. The coherence spectra were also shown in Figure 6.5. The variance spectrum of the observed temperature data showed concentrations of variances at periods above 80 years, 10 years (9.52), 5 years (4.88) and 3.5 years. The spectrum of the reconstructions from Group A and the three longest chronologies showed similar variances at about 10 years (9.52, 12.50 and 13.33), 5 years (4.76, 4.88) and 3.5 years (3.77, 3.92). It also showed a lack of variance at periods above 60 years. There was a peak around 6 years (5.88, 6.06) in both reconstructions but this was not found in the observed data. The variance spectrum of observed precipitation

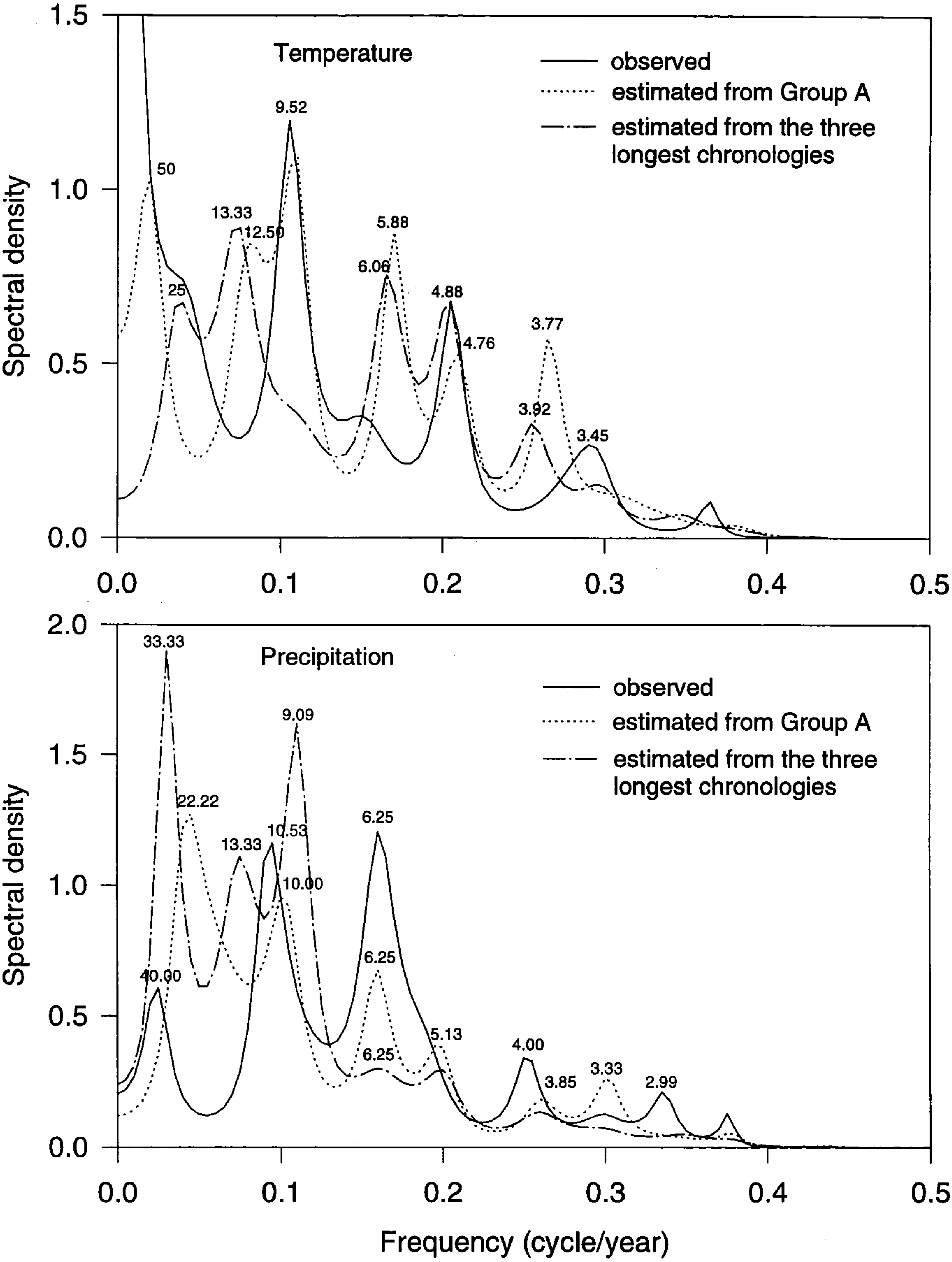


Figure 6.4 Spectral density of observed and reconstructed climate data.

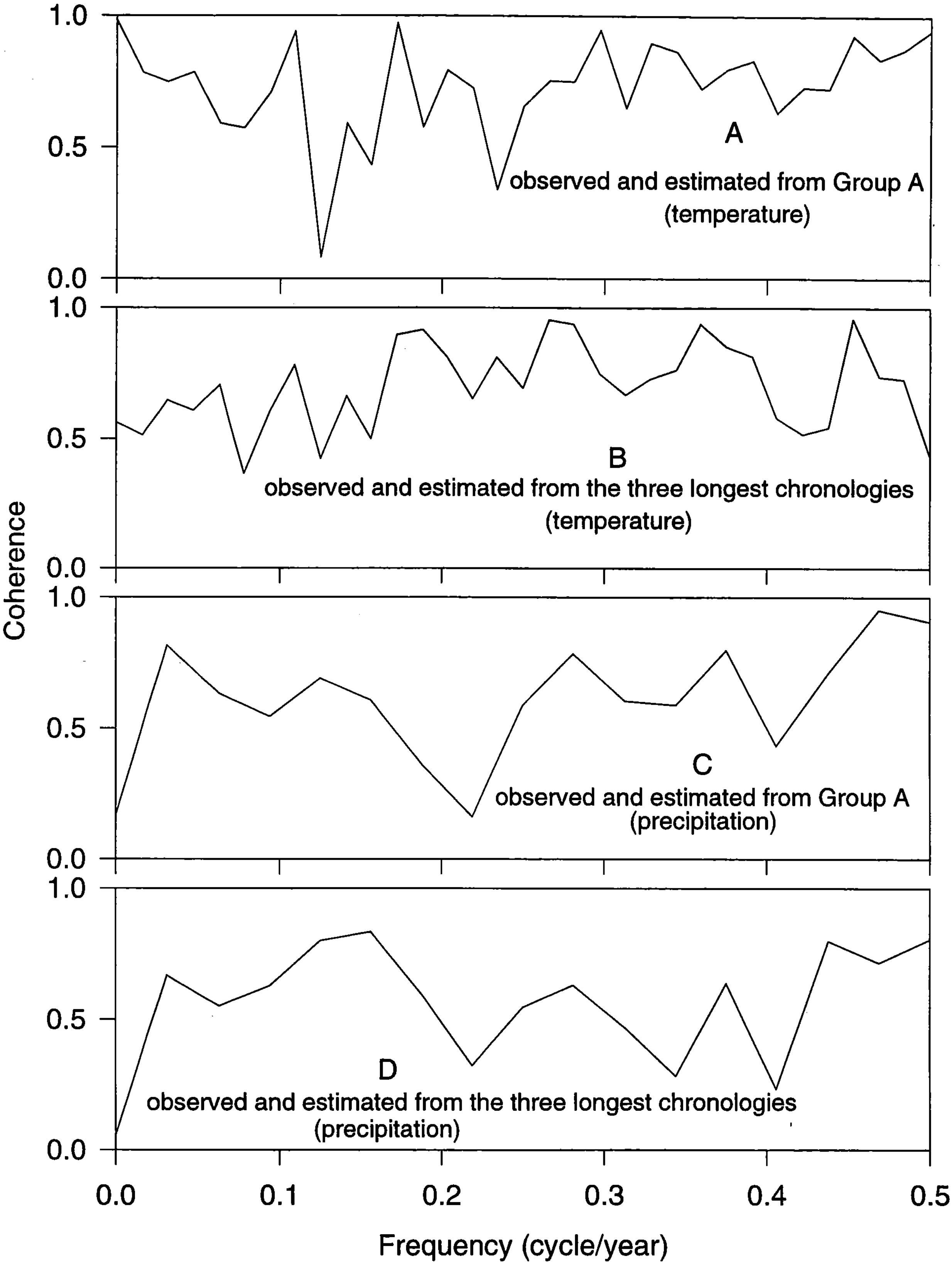


Figure 6.5 Spectral coherence of observed and reconstructed climate data.

showed variances at periods of around 40 years, 10 years, 6.25 years and 4 years. The reconstructions from both Group A and the three longest chronologies showed the same variance around 10 years (9.09, 13.33), 6.25 years and 4 years (3.85). The only differences were the low frequency reconstructions. Group A reconstructed a 22 year cycle but the three longest chronologies group reconstructed a very strong 33 year cycle. Differences were emphasised in the coherence diagram (Figure 6.5), where the most notable period with low common variance was around 8 years in temperature and around 4-5 years in precipitation. The reason for this was not known. However, the encouraging features were that all the periodicities in the observed data were reconstructed and both high and low frequency were reconstructed as expected (from having used a 2/3 spline filter for chronology standardisation).

6.5.5 Reconstructed climate

A) Temperature

The period since 1950 in New Zealand has been characterised by a mean temperature increase (Salinger 1982) which occurred in two phases; an initial increase centred around 1955 and the second centred around 1971 (Salinger, 1981). These are apparent in the observed 10-year-average February-March temperature series in Figures 6.6 and 6.7. Both increases have been modelled by the transfer function of Group A (Figure 6.6, above) but not the three longest chronologies (Figure 6.7, above). Both reconstructions from Group A and the three longest chronologies capture the cooler period in the early 1860's and early 1900's, but does not seem to capture the 1930's cooler period.

There are some general features in both reconstructions. Temperatures were highly variable in the early 1700's. Cool conditions became prevalent in the 1760s and around 1790. Temperatures then increased somewhat until the first decade of the 1800s. Then came a short period of cooling, and warming to the mid-1830s. From the longest reconstruction using the three longest chronologies back to 1450, the warmer years were around the 1460s, 1560s, 1600s and 1670s. The cooler years were around the 1640s and 1680s. The very warm individual years and periods were

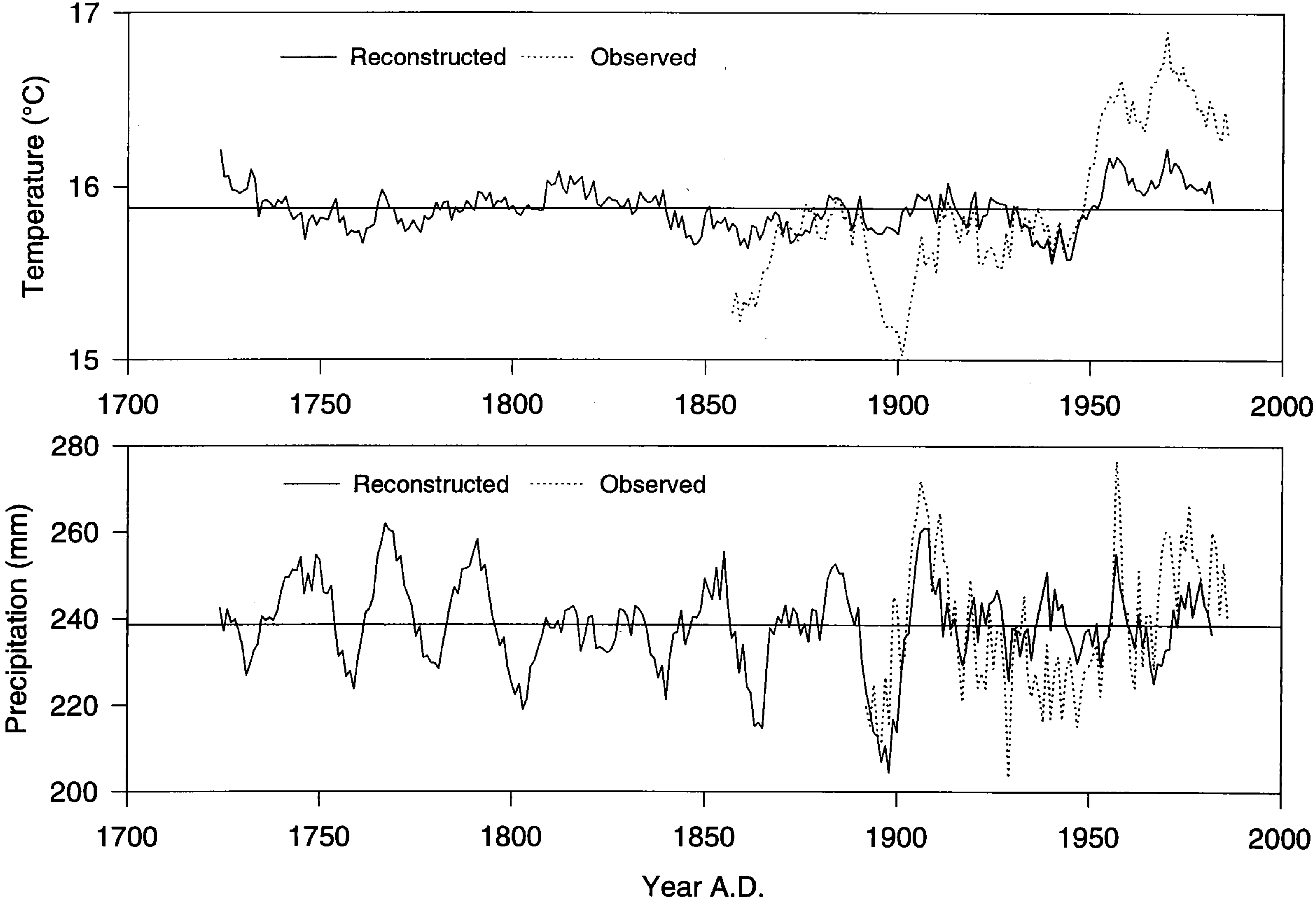


Figure 6.6 Comparison of variations on decade time scale (10 years average) of the recorded and reconstructed climate data from Group A.

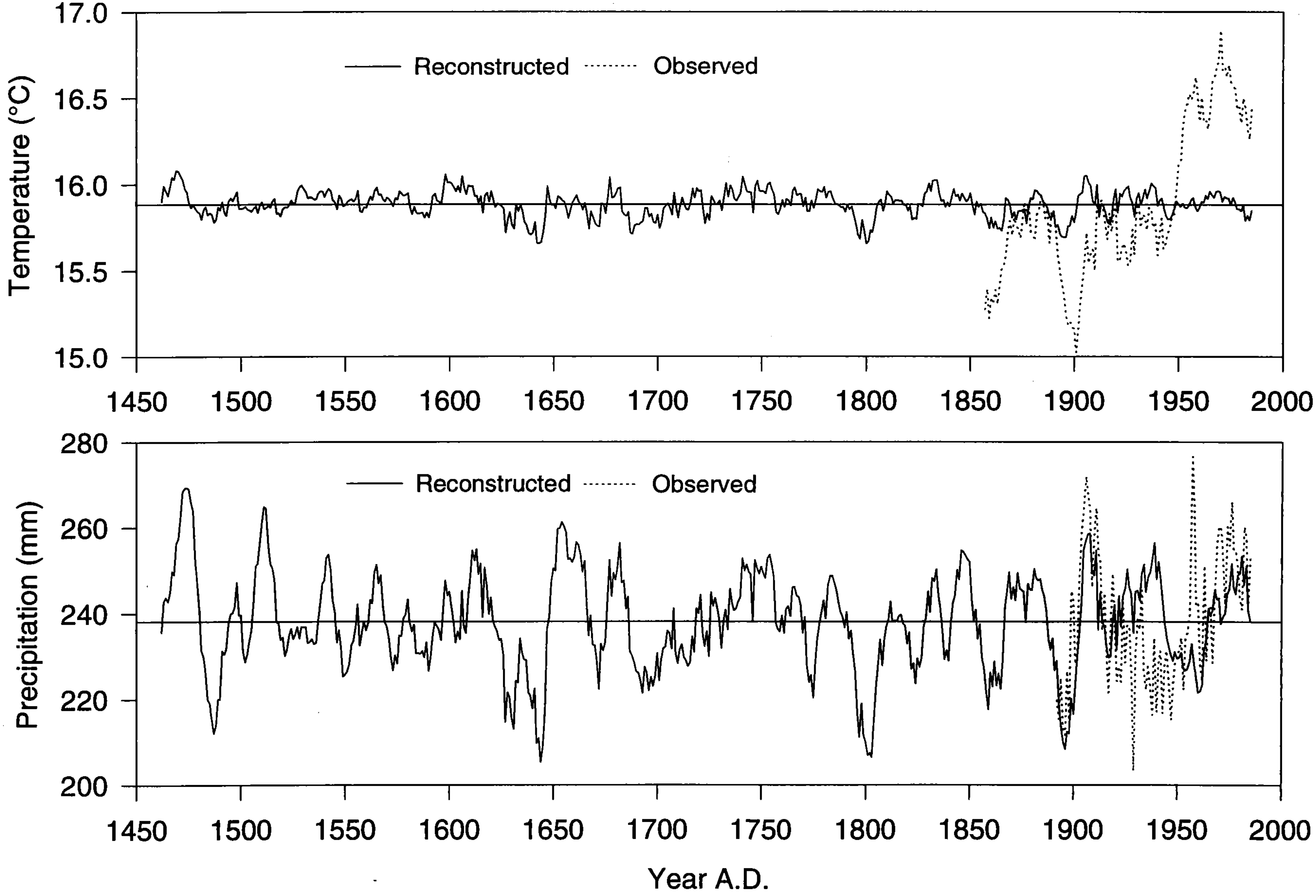


Figure 6.7 Comparison of variations on decade time scale (10 year average) of the recorded and reconstructed climate data from the three longest chronologies.

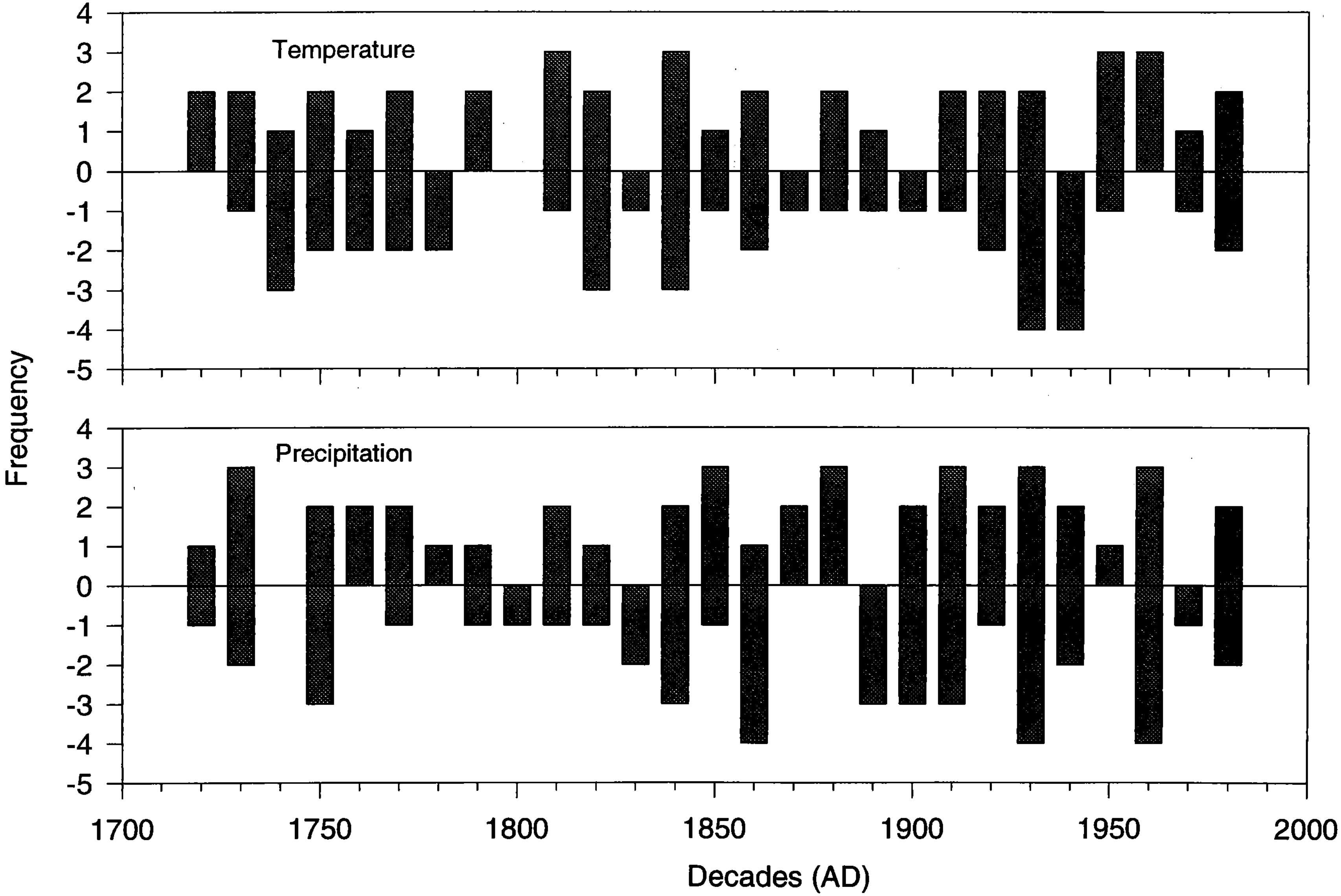


Figure 6.8 Frequency per decade of the reconstructed climate data from Group A greater than one standard deviation above or below average.

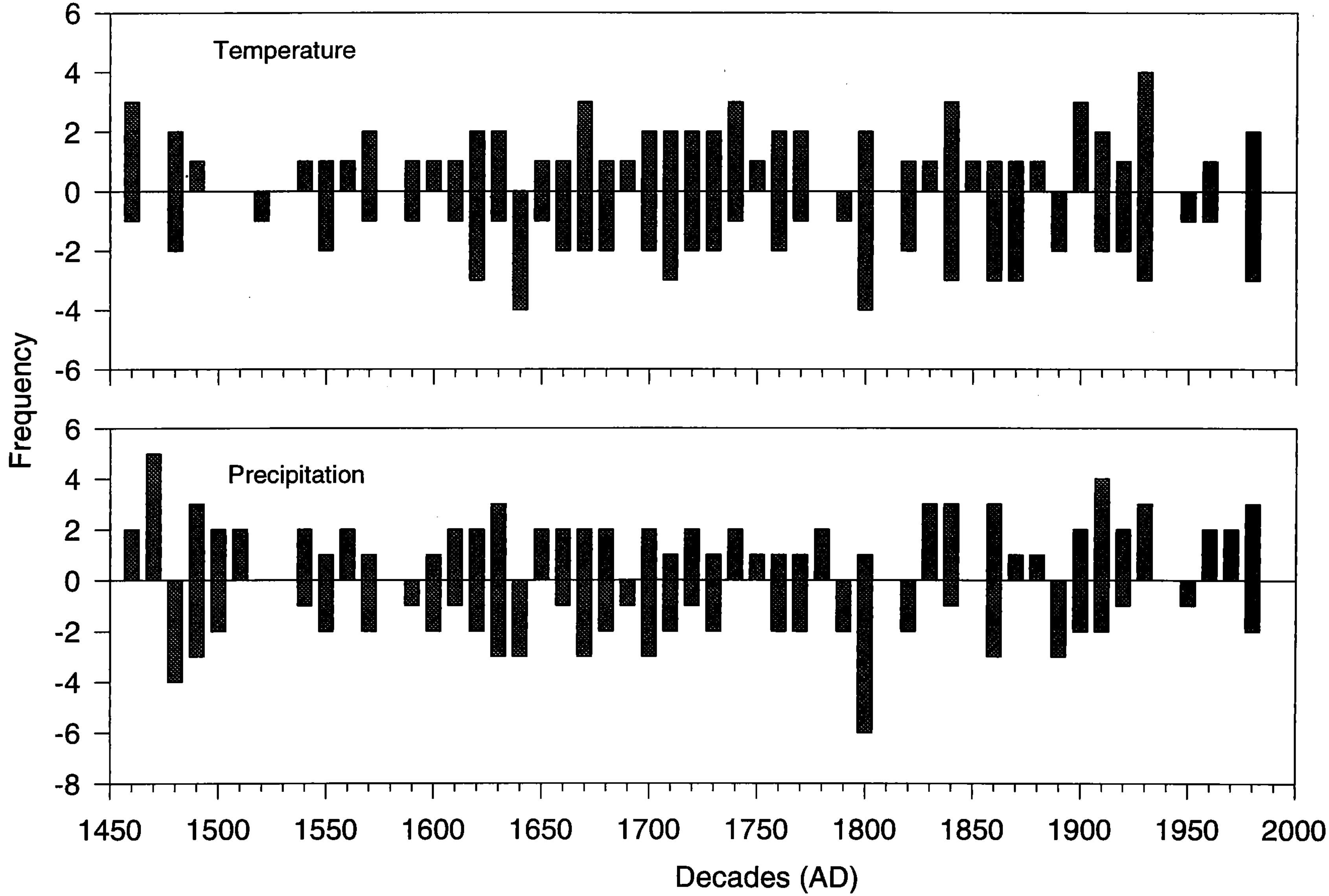


Figure 6.9 Frequency per decade of the reconstructed climate data from the three longest chronologies greater than one stardard deviation above or below average.

Table 6.4 Extreme February-March temperatures*

Individual years

Observed February-March temperature				Reconstructed from Group A chronology				Reconstructed from the three longest chronologies							
Warmest		Coldest		Warmest		Coldest		Warmest				Coldest			
Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.
1938	2.27	1853	-2.13	1916	1.52	1896	-1.38	1652	1.31	1678	1.01	1805	-.99	1841	-.69
1916	1.92	1912	-2.08	1935	1.42	1861	-1.08	1731	1.31	1611	.91	1641	-.89	1706	-.69
1957	1.67	1906	-1.98	1729	1.32	1866	-1.08	1552	1.22	1916	.91	1917	-.89	1861	-.69
1966	1.67	1898	-1.93	1720	1.12	1987	-1.08	1935	1.21	1673	.91	1987	-.79	1489	-.69
1990	1.67	1884	-1.68	1830	1.02	1804	-1.08	1622	1.21	1907	.91	1703	-.79	1728	-.69
				1826	.92	1772	-.98	1752	1.21	1803	.81	1896	-.79	1799	-.69
				1910	.92	1940	-.98	1830	1.11	1924	.81	1671	-.79	1647	-.59
				1883	.92	1936	-.98	1741	1.11	1717	.81	1627	-.79	1800	-.59
				1938	.92	1908	-.88	1682	1.11	1602	.81	1866	-.79	1827	-.59
				1790	.92	1931	-.88	1872	1.01	1633	.71	1689	-.69	1804	-.59

10-year-mean periods

Observed February-March temperature						Reconstructed from Group A chronology						Reconstructed from the three longest chronologies					
Warmest			Coldest			Warmest			Coldest			Warmest			Coldest		
Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD
1966-1975	1.02	.55	1897-1906	-.86	.67	1720-1729	.34	.55	1936-1945	-.33	.59	1465-1474	.19	.14	1639-1648	-.25	.32
1954-1963	.74	.62	1855-1864	-.66	.45	1966-1975	.32	.34	1857-1866	-.24	.58	1901-1910	.17	.44	1796-1805	-.22	.52
1977-1986	.62	.46	1890-1899	-.45	.65	1953-1962	.32	.33	1757-1766	-.22	.33	1737-1746	.17	.43	1892-1901	-.19	.26
						1808-1817	.22	.35	1868-1877	-.22	.29	1673-1682	.16	.57	1861-1870	-.17	.40
						1977-1986	.16	.39	1843-1852	-.20	.54	1594-1603	.15	.29	1684-1693	-.17	.26
						1909-1918	.14	.65	1742-1751	-.18	.45	1602-1611	.15	.40	1663-1672	-.16	.34
						1835-1844	.11	.42	1891-1900	-.15	.52	1829-1838	.15	.38	1623-1632	-.15	.35
						1762-1771	.10	.38	1772-1781	-.15	.43	1525-1534	.12	.12	1697-1706	-.14	.39
						1920-1929	.08	.54	1917-1926	-.11	.56	1748-1759	.12	.40	1483-1492	-.12	.31
						1790-1799	.08	.38	1906-1915	-.11	.48	1643-1652	.10	.46	1888-1897	-.12	.25

												1715-1724	.10	.28	1913-1922	-.11	.49
												1776-1785	.10	.23	1719-1728	-.11	.28
												1933-1942	.10	.49	1818-1827	-.10	.31
												1561-1570	.10	.18	1873-1882	-.10	.26
												1922-1931	.09	.37	1980-1989	-.09	.40
20-year-mean periods																	
Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD
1954-1973	.77	.63	1896-1915	-.55	.85	1956-1975	.24	.39	1931-1950	-.27	.64	1737-1756	.12	.43	1626-1645	-.16	.40
1972-1991	.55	.63	1853-1872	-.45	.72	1807-1826	.16	.45	1845-1864	-.19	.53	1828-1847	.12	.38	1694-1703	-.14	.28
						1720-1739	.15	.54	1747-1766	-.15	.41	1595-1614	.10	.32	1786-1805	-.14	.40
						1910-1929	.07	.62	1866-1885	-.12	.46	1524-1543	.10	.20	1653-1672	-.12	.32
						1825-1844	.06	.52	1896-1915	-.12	.48	1459-1478	.09	.23	1857-1876	-.11	.41
												1922-1941	.08	.45	1884-1903	-.10	.27
												1763-1782	.07	.30	1474-1493	-.07	.27
												1552-1571	.07	.35	1674-1693	-.07	.43
												1901-1920	.07	.47	1711-1730	-.06	.38
												1713-1732	.06	.46	1504-1523	-.06	.20
50-year-mean periods																	
Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD
1942-1991	.46	.68	1857-1906	-.36	.72	1937-1986	.07	.49	1844-1893	-.11	.49	1731-1780	.06	.40	1623-1672	-.09	.41
						1777-1826	.07	.42	1896-1945	-.09	.61	1576-1625	.05	.34	1851-1900	-.08	.33
						1720-1769	.04	.49	1738-1787	-.07	.43	1806-1855	.04	.32	1679-1728	-.06	.37
												1523-1572	.04	.28	1475-1524	-.04	.26
												1900-1949	.03	.43	1779-1828	-.03	.33

In the table, ano. means Anomaly (°C).
* February-March temperatures are shown as anomalies with respect to the mean of the whole period.

given in Table 6.4. The comparison between this reconstruction and other work will be further discussed in the next section.

B) Precipitation

Figures 6.6 and 6.7 (bottom) showed that the wet periods of the 1920s and 1970-1980 have been well reconstructed, but the dry period around the 1940s was not. The following dry periods were recognised in both reconstructions: 1490s, 1630-1650, 1800-1810, 1860-1870, 1890-1910. The wet periods were: 1480s, 1520s, 1655-1670, 1740-1755, 1850-1860s, 1910s. Individual extreme dry or wet years and extreme dry or wet periods are given in Table 6.5. For detailed data produced from this thesis refer to Appendix 4.

6.5.6 The comparison of reconstructed climate with other evidence

A) Temperature

Comparing with the temperature reconstruction of Palmer (1989), the first increase (1950's) was modelled, but the second increase (1970's) was not well reconstructed. The temperature model developed by Norton (1983a) and Norton *et al.* (1989) had the reverse problem (i. e. showed the warming in the 1970's but not so well in the 1950's). The reconstruction made by Salinger *et al.* (1994) captures the temperature increase after 1950, and a cooler period of temperatures in 1900's, 1920's and 1960's. The reconstructed temperature series from tree rings are plotted in Figure 6.10. A correlation analysis was made between all the different summer temperature reconstructions (Table 6.6). It should be noted that what constitutes the summer period varies between reconstruction models; Norton (1983a) and Norton *et al.* (1989) used December to March; Palmer (1989) used January to March; Salinger *et al.* (1994) used November to March; and Cook *et al.* (1992) used November to April. In this study the months February to March were used. Consequently, slight differences among the reconstructed series might be expected purely because of slight differences in selected season length. The significance of most of the

Table 6.5 Extreme March-April precipitation*

Observed March-April precipitation				Reconstructed from Group A chronology				Reconstructed from the three longest chronologies							
Wettest		Driest		Wettest		Driest		Wettest				Driest			
Individual years															
Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.	Year	Ano.
1962	238.72	1889	-146.28	1935	130.59	1861	-147.3	1652	138.29	1907	92.09	1671	-97.81	1801	-72.21
1904	189.72	1963	-146.28	1904	94.09	1933	-93.31	1731	125.39	1872	88.79	1917	-93.11	1921	-70.71
1935	152.72	1952	-132.28	1872	90.09	1896	-92.91	1752	117.89	1830	83.09	1827	-82.91	1703	-70.41
1968	142.72	1940	-129.28	1962	88.49	1963	-91.81	1622	109.19	1916	80.19	1861	-80.91	1841	-68.71
1938	139.72	1958	-127.28	1948	79.09	1845	-73.71	1935	107.99	1512	77.79	1641	-79.41	1899	-67.81
				1907	78.69	1866	-72.51	1988	106.39	1602	77.39	1483	-79.01	1919	-66.91
				1961	68.69	1850	-72.41	1611	98.19	1662	75.29	1730	-74.91	1900	-66.71
				1765	68.29	1947	-72.21	1682	95.19	1552	74.39	1799	-74.41	1551	-65.41
				1916	66.79	1728	-71.21	1741	93.99	1918	70.89	1863	-74.41	1777	-65.21
				1865	65.49	1899	-70.71	1678	93.99	1904	69.09	1898	-73.41	1647	-64.01

10-year-mean periods																	
Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD
1953-1962	39.32	109.5	1925-1934	-33.98	61.59	1763-1772	23.35	29.73	1894-1903	-34.12	38.04	1470-1479	31.36	15.74	1640-1649	-32.67	25.11
1902-1911	34.62	88.26	1892-1901	-25.58	68.99	1903-1912	22.41	40.14	1861-1870	-23.91	56.23	1507-1516	26.84	24.85	1799-1808	-31.60	42.62
1972-1981	28.82	57.05	1943-1952	-22.08	76.51	1787-1796	19.68	14.41	1799-1808	-19.66	24.40	1650-1659	23.24	43.17	1892-1901	-29.60	33.80
						1851-1860	16.92	30.96	1836-1845	-17.13	34.72	1904-1913	20.62	39.09	1483-1492	-25.89	33.17
						1953-1962	16.47	38.36	1755-1764	-14.75	35.43	1935-1944	18.38	37.11	1627-1636	-24.96	33.34
						1745-1754	16.08	32.80	1963-1972	-13.45	44.24	1678-1687	18.37	47.65	1855-1864	-20.40	35.22
						1880-1889	14.12	29.68	1925-1934	-12.78	43.62	1609-1618	16.92	38.11	1771-1780	-17.70	25.59
						1935-1944	12.21	51.58	1727-1736	-11.77	39.43	1842-1851	16.70	30.32	1689-1698	-16.62	25.15
						1975-1984	10.50	26.04	1777-1786	-10.13	17.67	1538-1547	15.70	22.50	1956-1965	-16.44	22.11
						1922-1931	8.19	33.97	1949-1958	-9.52	24.93	1750-1759	15.64	38.20	1668-1677	-15.70	37.36
												1977-1986	15.35	32.76	1820-1829	-14.35	35.47
												1737-1746	14.78	37.14	1545-1554	-12.70	38.47

												1661-1670	14.16	31.58	1586-1595	-11.37	19.48
												1561-1570	13.33	21.52	1569-1578	-11.30	28.55
												1877-1886	12.36	21.84	1711-1720	-10.30	32.07
20-year-mean periods																	
Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD
1968-1987	18.37	62.59	1925-1944	-18.48	83.21	1736-1755	11.35	29.61	1894-1903	-15.60	37.89	1648-1667	19.74	36.27	1626-1645	-21.26	36.81
1901-1920	17.17	79.88	1888-1907	-11.58	87.13	1762-1781	9.23	28.50	1861-1880	-13.08	49.53	1463-1482	18.78	23.35	1788-1807	-17.17	37.93
1943-1962	8.62	99.29	1950-1969	-5.53	106.1	1901-1920	8.68	47.49	1799-1818	-10.77	28.90	1739-1758	14.06	37.34	1884-1903	-14.96	31.59
						1869-1888	8.62	34.78	1826-1845	-7.59	33.66	1830-1849	12.23	37.65	1687-1706	-12.77	30.45
						1841-1860	6.17	43.79	1963-1982	-5.71	37.93	1496-1515	12.23	32.37	1946-1965	-12.49	23.13
												1922-1941	11.36	36.51	1483-1502	-11.23	39.25
												1869-1888	10.60	27.62	1711-1730	-9.17	35.33
												1597-1616	10.08	36.42	1852-1871	-8.52	36.00
												1966-1985	8.51	31.36	1571-1590	-8.48	26.61
												1901-1920	7.89	49.39	1546-1565	-7.08	31.30
50-year-mean periods																	
Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD	Period	Ano.	SD
1941-1990	6.08	81.75	1917-1966	-7.04	90.59	1749-1798	6.67	30.40	1854-1903	-6.26	44.18	1721-1770	6.48	39.59	1793-1842	-7.92	36.78
						1902-1951	3.91	47.97	1796-1845	-5.55	31.41	1464-1517	6.37	35.58	1689-1738	-6.76	36.98
						1810-1859	1.83	35.47	1931-1980	-1.79	45.25	1902-1951	6.04	41.21	1852-1901	-6.69	35.86
												1648-1697	5.65	40.85	1600-1649	-6.39	41.02
												1576-1625	3.35	34.18	1547-1596	-4.79	29.50

In the table, ano. means Anomaly (mm).
* March-April precipitation are shown as anomalies with respect to the mean of the whole period.

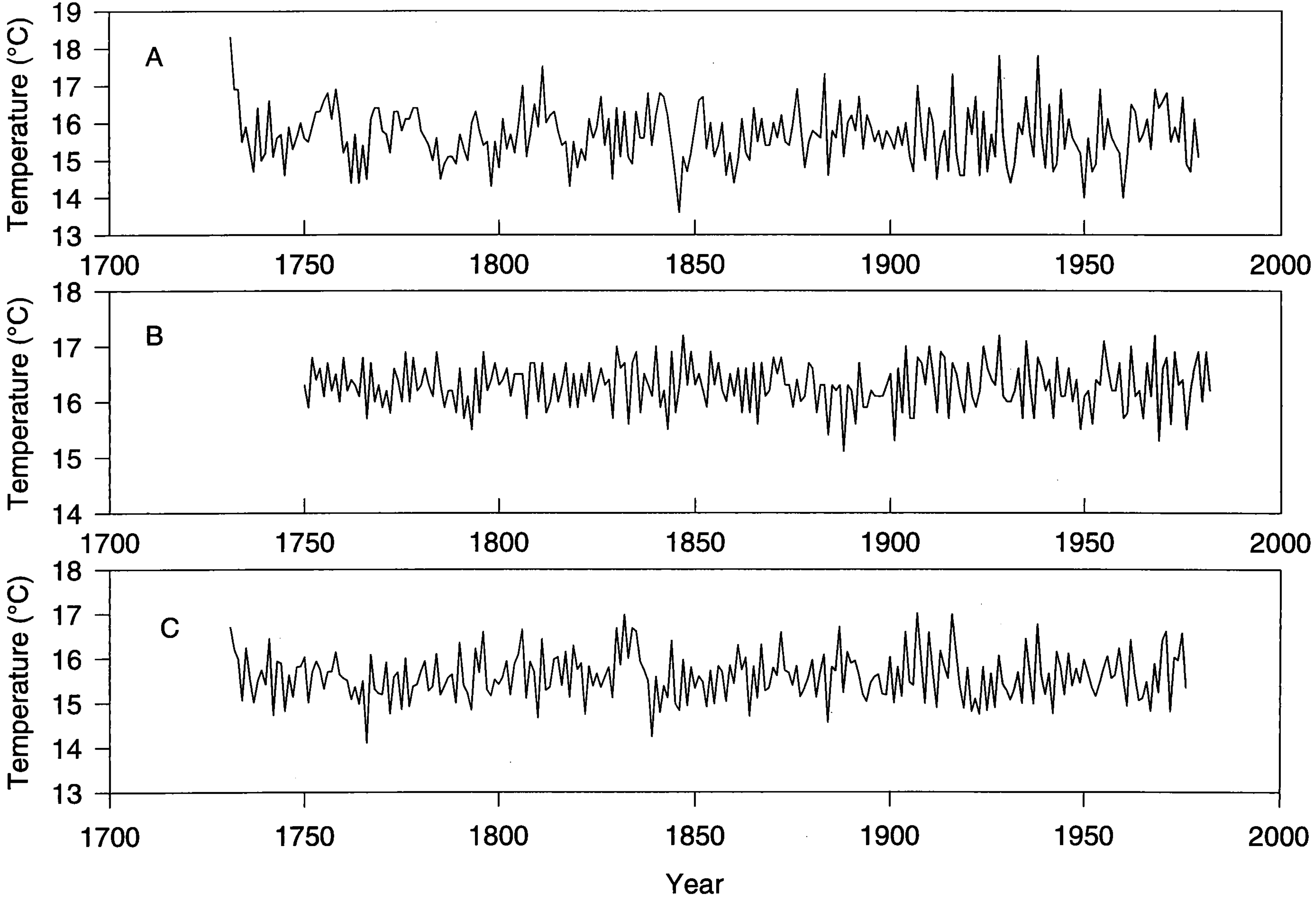


Figure 6.10A Comparison of reconstructed temperature series. The temperature reconstructions based on: **A.** *Nothofagus spp.* by Norton *et al.* (1989). **B.** *Phyllocladus spp.* by Palmer (1989). **C.** Early model from mixed species by Salinger *et al.* (1994).

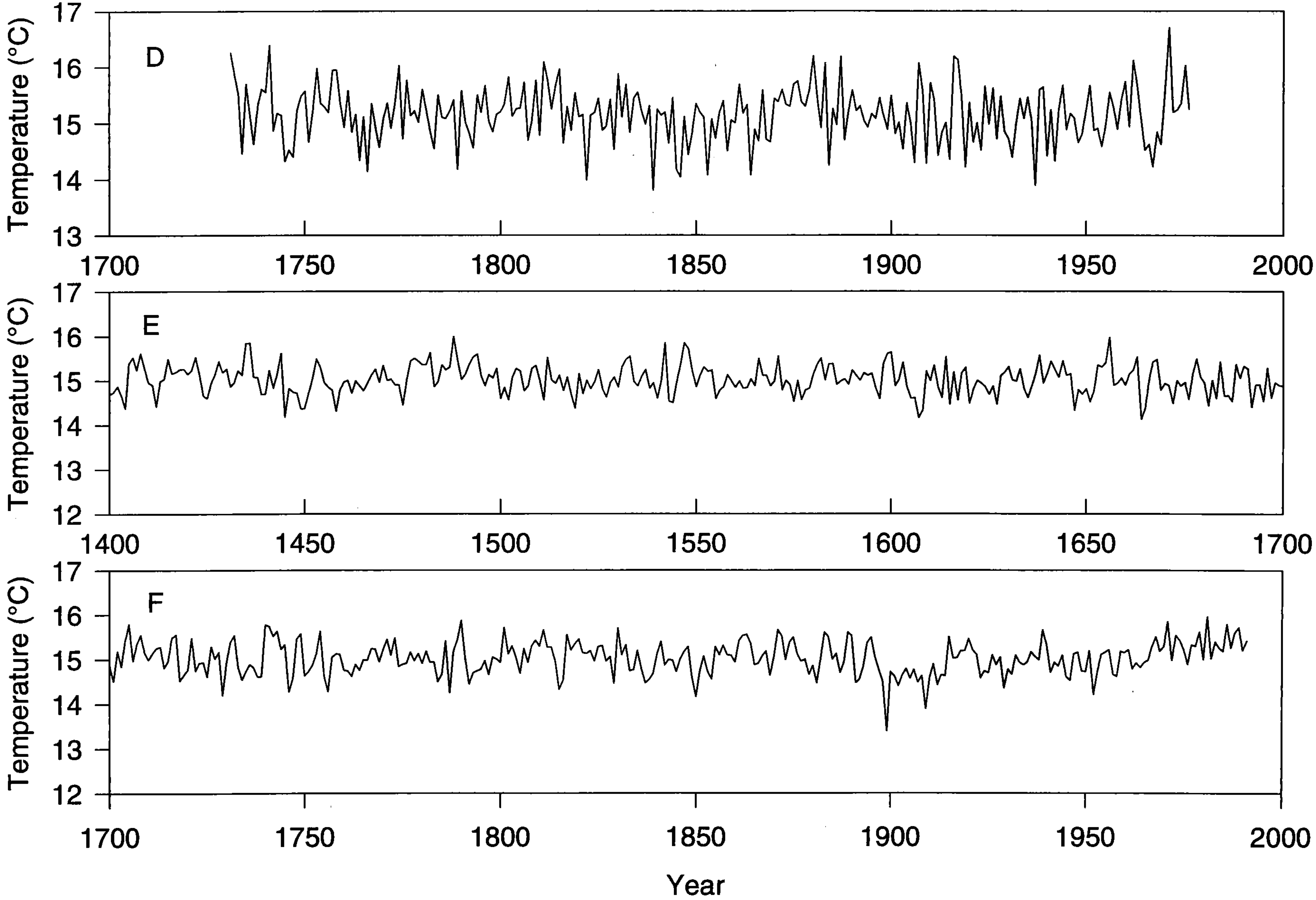


Figure 6.10B Comparison of reconstructed temperature series. The temperature reconstructions based on: **D.** Late model from mixed species by Salinger *et al.* (1994). **E & F.** *Lagarostrobus franklinii* by Cook *et al.* (1992).

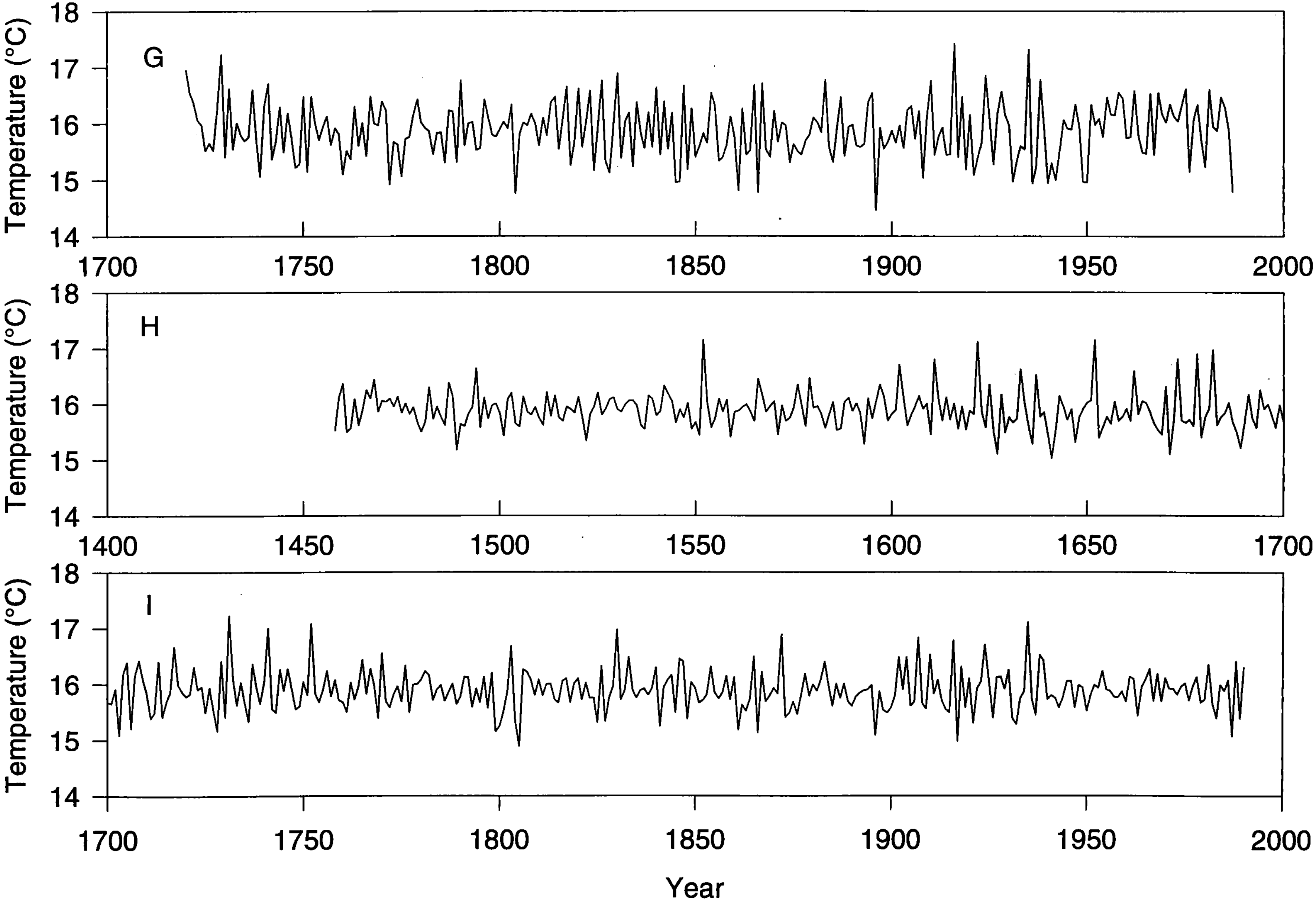


Figure 6.10C Comparison of reconstructed temperature series. The temperature reconstructions based on: **G.** Group A *Libocedrus bidwillii* chronologies by this thesis. **H & I.** the three longest *Libocedrus bidwillii* chronologies by this thesis.

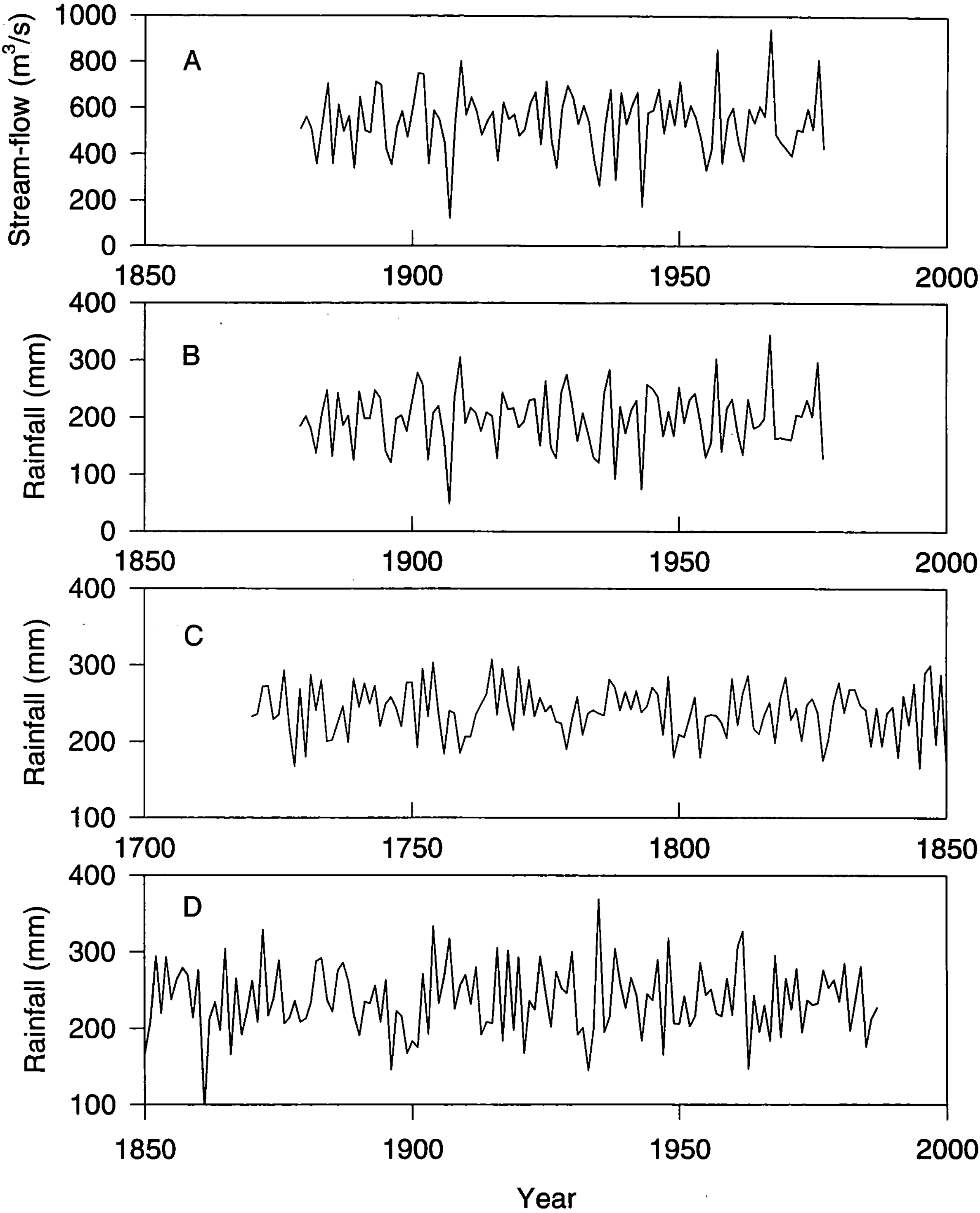


Figure 6-11A Comparison of reconstructed riverflow and rainfall. **A.** Hurunui riverflow from *Nothofagus spp.* by Norton (1987). **B.** Coleridge rainfall from *Nothofagus spp.* by Norton (1987). **C & D.** Rainfall from *Libocedrus bidwillii* (Group A) by this thesis.

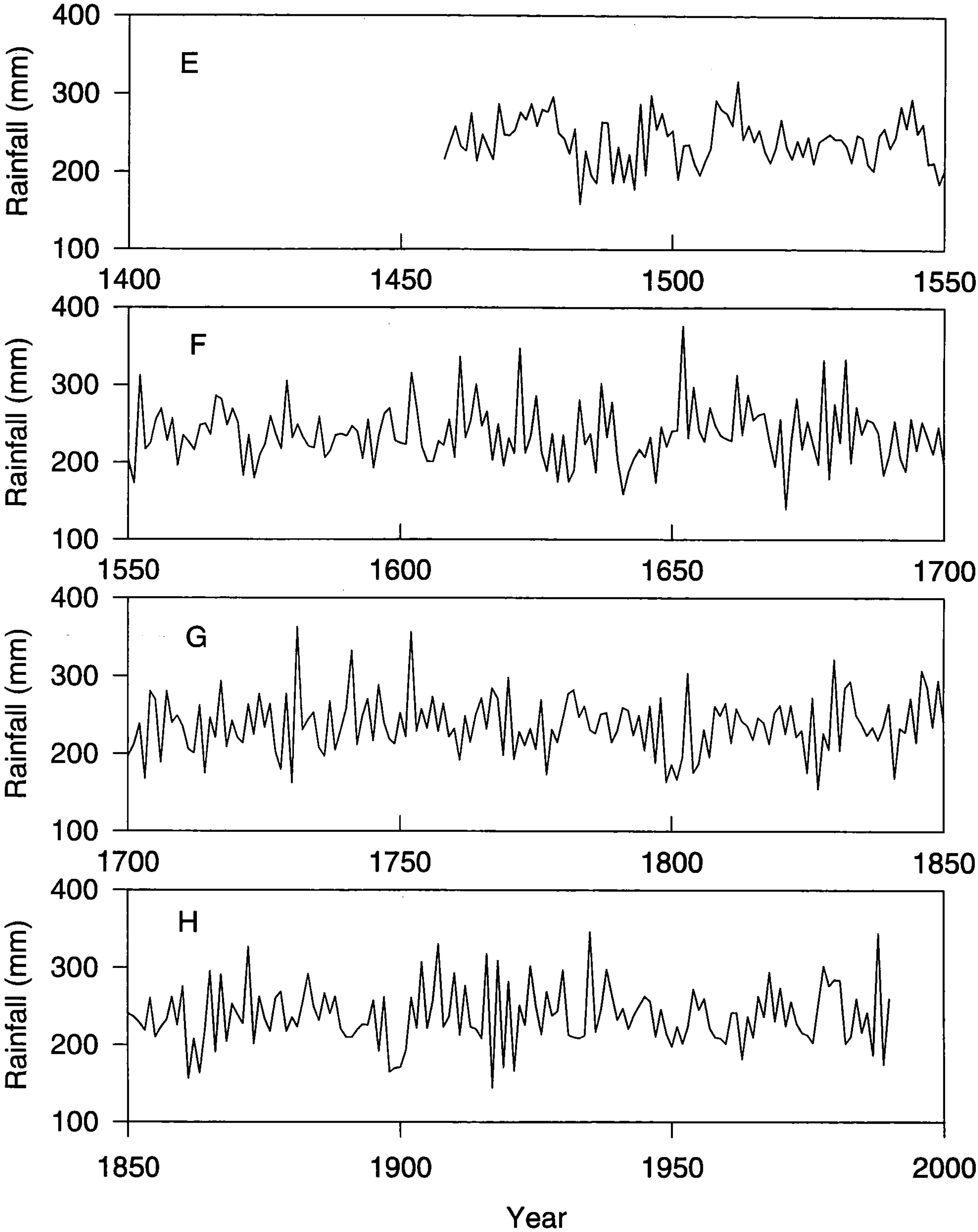


Figure 6.11B Comparison of reconstructed riverflow and rainfall. **E-H.** Rainfall from Libocedrus bidwillii (the three longest chronologies) by this thesis.

Table 6.6 Correlation coefficients between New Zealand and some Australia summer temperature reconstructions from tree-ring*

	THR[1]	GRA[2]	Palmer[3]	Norton[4]	Salinger-early[5]	Salinger-late[5]	Cook[6]
		-0.100	0.295	0.681	-0.302	0.167	0.101
THR		0.2517	0.0025	0.0001	0.0007	0.0655	0.0438
		133	103	122	122	122	395
	0.499[a]		-0.205	0.262	0.671	0.569	0.499
GRA	0.0001[b]		0.0380	0.0035	0.0001	0.0001	0.0001
	133[c]		103	122	122	122	133
	0.205	0.352		-0.176	0.376	-0.494	0.460
Palmer	0.038	0.0003		0.0231	0.0001	0.0001	0.0001
	103	103		166	113	168	168
	0.124	0.339	0.315		0.044	0.655	-0.160
Norton	0.175	0.0001	0.0001		0.6201	0.0001	0.0294
	122	122	166		132	185	185
	0.213	0.359	0.628	0.418		0.121	0.255
Salinger-early	0.019	0.0001	0.0001	0.0001		0.168	0.0017
	122	122	113	132		132	149
	0.135	0.277	0.480	0.614	0.772		0.067
Salinger-late	0.139	0.0020	0.0001	0.0001	0.0001		0.3580
	122	122	168	185	132		190
	0.088	0.117	0.045	0.138	0.218	0.208	
Cook	0.0823	0.1782	0.5635	0.0619	0.0075	0.0039	
	395	133	168	185	149	190	

Note:

* The left bottom half is the correlation between reconstructed temperature itself; the right top half is the correlation between 50-year running mean of the reconstructed temperature.

1. Temperature reconstructions based on the three longest *Libocedrus bidwillii* chronologies by this thesis.
2. Temperature reconstructions based on Group A *Libocedrus bidwillii* chronologies by this thesis.
3. Temperature reconstructions based on *Phyllocladus spp.* by Palmer (1989).
4. Temperature reconstructions based on *Nothofagus spp.* by Norton *et al.* (1989).
5. Temperature reconstructions based on mixed species by Salinger *et al.* (1994). "early" refers to 1863-1920 data being used for calibration and "late" to 1920-1976 for calibration with the corresponding other halves being used for verification.
6. Temperature reconstructions based on *Lagarostrobus franklinii* from Tasmania by Cook *et al.* (1992).

a. Correlation coefficient.
b. Probability that the value could occur by chance.
c. The number of years, which varies because intervals used for calibration have been omitted. This was done in order to prevent the possibility of biased results especially when the same period of recorded temperatures was used to develop both temperature reconstruction series (i.e. confounded results).

correlations between all the different reconstructed summer temperature series clearly demonstrates the potential for the inclusion of a much greater network of chronologies. An interesting trend seen in the table is that the correlations of Group A *Libocedrus bidwillii* chronologies (GRA) with all other NZ reconstructions are significant at the 1% level. The three longest *Libocedrus bidwillii* chronologies (THR) with Palmer and Salinger-early were significant at the 5% level, but not significant for the correlations with Norton and Salinger-late. This was probably because the three longest chronologies (THR) came from the central North Island, Palmer's reconstruction was also based on the central North Island chronologies but Norton's reconstruction was based on South Island chronologies. The geographical differences possibly contributed to the different correlations. Salinger's reconstruction was based on a nation-wide, multiple species data-base. The significance between THR and Salinger-early and the lack of significance between THR and Salinger-late might be due to the poor climate response of old *Libocedrus bidwillii* trees. Figure 6.12 shows the response function for the chronologies developed from different sized trees at site RUC. Most of the response functions are similar but the chronology developed from the big trees has fewer significant temperature months. This result confirmed that the climate response of 'big trees' was poorer than 'small trees' in *Libocedrus bidwillii*. There were no young (small) trees included in the three longest chronologies (refer to Chapter 4). Therefore, perhaps it is not strange that a transfer function only based on the last few decades (Salinger-late) was not significant with the reconstructions from the three longest chronologies derived from only 'big' trees.

Comparison with the long-term temperature reconstruction from Huon pine (*Lagarostrobos franklinii*) tree rings from a subalpine site in western Tasmania (Cook *et al.* 1992) has been carried out in the same way as the above. The long-term mean of this reconstructed November-April temperature since AD 900 is 14.99°C with a standard deviation of ±0.397°C. Eight of the warmest and coldest 25-year periods in the temperature reconstruction were described by Cook *et al.* (1992). Four warm periods out of the eight were within our reconstruction time span: 1965-1989; 1476-1500; 1855-1879; 1808-1832. The three coldest out of the eight periods were also in our reconstruction time span: 1890-1914; 1604-1628; 1664-1688.

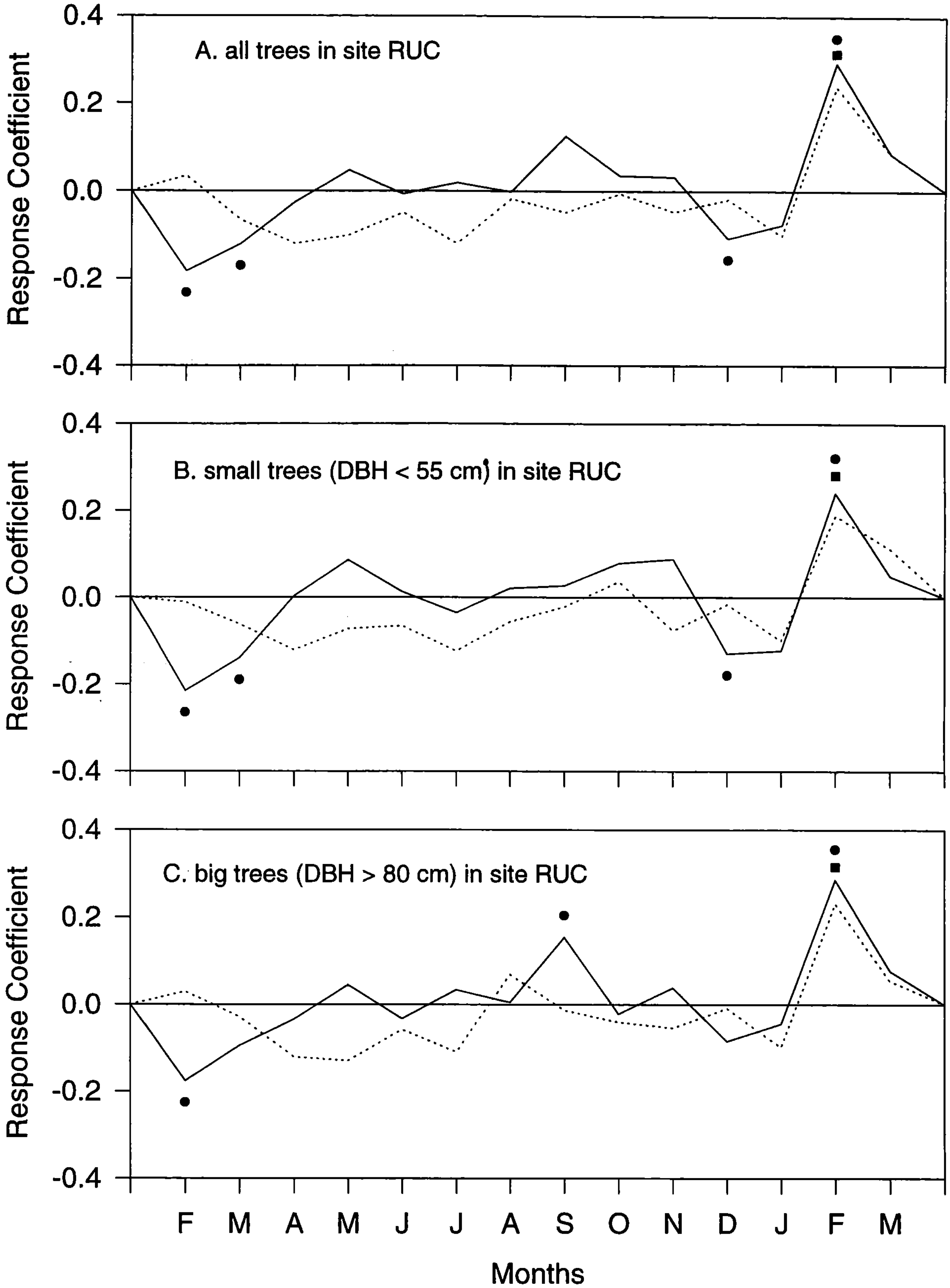


Figure 6.12 The comparison of the response function for the chronologies developed from different size trees in site RUC. —— Temperature ········ Precipitation
• Temperature significant at 95% ▪ Precipitation significant at 95%

Table 6.7 The comparison of tree-ring reconstructions with icebergs and glacial evidence

	Tree-ring reconstructions[1]	Extreme northern drift of iceberges[2]		Glacier expansion periods in the Southern Alps	
		Various parts of the southern ocean	Australasian sector	Descriptions[3]	Evidences
20th century	Warm periods: 1910-1929, 1956-1975; Cold years: 1908, 1931, 1936, 1940	1948, 1935-39, 1929-31, 1922-23, 1904-12	1948, 1931, 1923	Major recession, broken by minor advances about 1908, 1930, 1950 and 1970; the glacier shrinkage from about AD 1900 to at least AD 1984 has been the most profound for at least the last 3500 years[4].	Observed[3]
19th century	Cold periods: 1840-1852, 1857-1866, 1891-1900	1888-99, 1865-69, 1861, 1852-60, 1850, 1844, 1839-40, 1832-34	1891-98, 1867, 1853-55, 1840	Glaciers were enlarged during advances about mid-century and 1890.	Observed and radiocarbon dates NZ-5504 & NZ-5506 < 250 radiocarbon year BP from Mount Cook[4]
18th century	Cold periods: 1742-1751, 1757-1766	1798, 1789, 1772-75		Possibly glaciers were enlarged about mid-century	Lichen dates 170 BP from Arrowsmith Range[5]
17th century	Cold periods: 1626-1645, 1653-1672			Glaciers underwent at least one substantial advance and possibly others this century	Radiocarbon dates NZ-5330 343±56 BP from Mount Cook[4]
16th century	Cold period: 1504-1523			An advance occurred of the Tasman Glacier, Mount Cook early in the century	Radiocarbon date NZ-5330 343±56 BP[4] and Lichen dates 410 BP from Arrowsmith Range[5]
15th century	Only reconstructed back to 1548 AD			At least one advance occurred in several glaciers about the beginning of the century	Radiocarbon date NZ-687 AD 1380±50, NZ-4016 AD 1400 ± 70[3] and Lichen dates 480 BP from Arrowsmith Range[5]

Sources:
1 This thesis (refer to Table 6.4)
2 Burrows, 1976
3 Burrows, 1982
4 Burrows, 1989
5 Burrows *et al.* 1990

The warmest and coldest 20-year periods from *Libocedrus bidwillii* were given in Table 6.4. The warmest periods matching the Tasmania Huon pine reconstruction were: 1956-1975; 1807-1826; 1825-1844; 1459-1478. The coldest periods were also well matched in the Huon pine reconstruction: 1896-1915; 1626-1645; 1653-1672; 1884-1903. The correlations of *Libocedrus bidwillii* reconstructions with Huon Pine reconstruction are not significant, but the correlations between long term trends (50 year running mean) are significant at 5% (THR) or 1% (GRA) level (Table 6.6). These results imply there are similar long-term climate trends in the region and are very encouraging.

The only data available for last millennium as a whole in New Zealand are the iceberg record, the glacial chronology and the speleothem (and tree) palaeo-temperature estimates. The dating of glacial episodes is not precise prior to the late 19th century, even when radiocarbon dates are available. Probably the best-dated sequence is that for tree paleo-temperatures and that is not yet published. There is some uncertainty about the precision of timing of the older part of the speleothem temperature curve (prior to 1600 AD) because it is dated by the radiocarbon method and also because the curve is for 50-year running means (Burrows & Greenland, 1979).

On the basis of the glacier evidence, there appears to have been cool periods in the late 10th to early 11th century, early 12th century, mid-late 13th century, early 15th century, early 16th century, also in the 17th century, possibly in the 18th century and in the middle and late 19th century (Burrows, 1982). The *Agathis australis* cellulose $\delta^{13}C$ curve (Grinsted & Wilson, 1979) indicates that the warmest periods probably occurred around A.D. 1000, A.D. 1200, A.D. 1500, and A.D. 1800. The $\delta^{13}C$ record indicates cold periods in the late 11th (c. A.D. 1070), late 13th (c. A.D. 1290), 17th (c. A.D. 1650), and late 19th (c. A.D. 1870 onwards) centuries. Somewhat less cold periods are indicated for the mid 18th (c. A.D. 1750), and possibly the late 14th (c. A.D. 1370) centuries. This interpretation agrees well with Burrow's interpretation of the glacial data and iceberg records (Table 6.7).

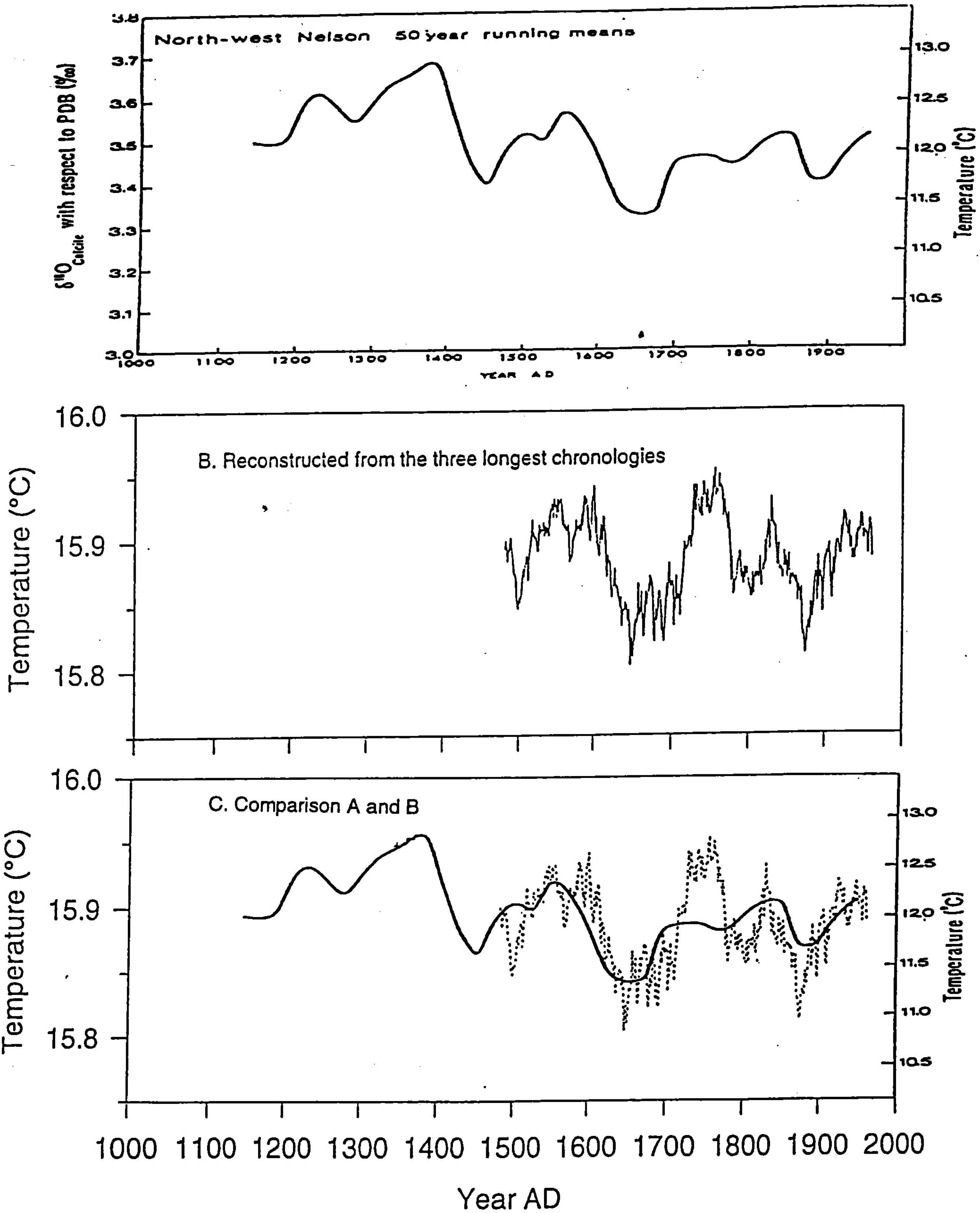


Figure 6.13 The comparison of speleothem palaeotemperature curve and the temperature reconstructed from the three longest chronologies. **A** (top): speleothem palaeotemperature curve from a cave in Nelson (After Wilson *et al.* 1973). **B**. Feb.-Mar. temperature reconstructed from three *Libocedrus bidwillii* chronologies. **C**. Comparison A and B. In C, the solid line was speleothem palaeotemperature curve, dashed line is the temperature reconstructed from tree-ring chronology (50 years mean).

Other information concerning climate changes in New Zealand during the last millennium arises from measurements of $^{18}O/^{16}O$ ratios in speleothems. The speleothem palaeotemperature curve from a cave in Nelson was shown in Figure 6.13 (Wilson *et al.* 1973; Burrows, 1982). The 50 years mean of reconstructed temperature from the three longest chronologies is also shown in Figure 6.13. The reconstructed temperature from tree-ring data (Appendix 4) agree with all the above evidence, especially with the speleothem palaeotemperature curve (Figure 6.13C).

B) Precipitation

The only reconstructed precipitation using dendroclimatic methods in New Zealand was Norton's work (1987). The reconstructed rainfall and riverflow from tree rings are shown in Figure 6.11. Norton's reconstructions extend the precipitation of Canterbury back to AD 1879. The current research reconstructed NZ average rainfall based on a number of chronologies which makes it difficult to compare with the reconstruction of Norton (1987).

Precipitation data from other sources have been difficult to find. Data on varying rates of changes of streambeds in Hawkes Bay suggest major periods of erosion and deposition possibly about AD 1450, about AD 1650 between AD 1800 and AD 1850 and about AD 1890 (Burrows & Greenland, 1979). Other reasonably good information comes from Healey's (1975) work on Rotorua's closed basin lakes (Burrows, 1982). Dates of Maori sites, now below lake level, indicate low levels in the 17th and 18th centuries and they were also low in the 19th century. The lakes rose to an all time high about 1970 as a result of increasing precipitation.

The precipitation reconstructed from tree-ring data showed above average precipitation in the period of 1650-1659, 1842-1851, 1904-1913 (Table 6.5), this matched with the streambed data from Hawkes Bay. The reconstructed data also showed that there was below average precipitation in the period of 1600-1649, 1689-1738, 1793-1842, 1852-1901 but above average in 1902-1951 (Table 6.5). This is a similar pattern to the closed basin lake levels in Rotorua.

6.6 Chapter Conclusions

1. Group A chronologies, the three longest chronologies from Group A and Group B chronologies were selected to reconstruct past climate. PVP selection of the PCA analysis resulted in more than 90% of variance retained and 1/2 to 1/3 of variables reduced.

2. Comparison of the climate data from different seasons with the three groups of chronologies was tried using the bootstrap transfer function. Average February-March temperature and total March-April precipitation were finally selected as the reconstructed variables based on the independent verification results.

3. In the general transfer function, there was a large difference in the correlation coefficient and RE value dependending on which period was used for calibration. The bootstrap method solved this problem because it is calibrated over the whole period and still had independent verification.

4. The temperature reconstruction from Group A is better than that of the three longest chronologies even though both transfer functions are significant. Both of the groups reconstructed the hot years better than cold years. The spectrum of the reconstructions from the two groups showed similar variance with observed temperature at about 10 years, 5 years and 3.5 years.

5. In the precipitation reconstruction, Group A reconstructed more extreme years than that of three longest chronologies. But the reconstruction from three longest chronologies has a higher match ratio with observed data than that of Group A. The reconstructions from the two groups show the same variance with observed rainfall data around 10 years, 6.25 years and 4 years. All the periodicities in the observed data were reconstructed and both high and low frequency were reconstructed as expected.

6. The warming periods identified from the reconstructed temperature series are: 1460s, 1560s, 1610s, 1670s, 1790-1810 and 1830s. The cooling periods are:

1640s, 1680s, 1760-1790, 1810-1820. Extremely warm years and cold years were also identified from this research.

7. The following dry periods were identified in both precipitation reconstructions: 1490s, 1630-1650, 1800-1810, 1860-1870. The wet periods were: 1480s, 1520s, 1655-1670, 1740-1755, 1850-1860s. The severe drought and very wet years were also recognised.

8. The reconstructed temperature series was highly correlated with other reconstructions from tree-rings. It also agrees well with glacial evidence, isotope evidence from tree ring data and the speleothem palaeotemperature curve. The reconstructed precipitation had a similar pattern with data from streambeds in Hawkes Bay and the Rotorua closed basin lake levels.

CHAPTER SEVEN
FINAL DISCUSSION AND CONCLUSIONS

7.1 Final discussion

This research aimed to illustrate the potential usefulness of *Libocedrus bidwillii* for dendroclimatic research.

The opportunity for such a project arose mainly from the work of LaMarche *et al.* (1979a) and Norton (1983a). They had already developed eleven chronologies from this species and one was the longest chronology in New Zealand extending back to AD 1256. However, no climate reconstruction had been attempted.

Previous dendroclimatological work in New Zealand had concentrated on different species. Such work had shown that practical difficulties were associated with using only statistical models and not investigating the growth-physiology of each species. In this project, the seedling growth under different environments was studied. The seasonal growth pattern and the relationship between growth and environmental factors were discussed. This helped to interpret the response function analyses. One disappointment was that the electronic dendrometers set up in the field failed to provide any conclusive information. However, the results were of some use in showing general periods of growth and have been included as an appendix (Appendix 1).

In order to improve the available tree-ring network, new site chronologies were needed. The eleven chronologies produced by previous workers also needed to be updated so that a longer response function period could be applied. The work reported in this thesis therefore, included the sampling, preparation, crossdating and measuring of new ring-width data, and, as a result, twelve new sites and five updated chronologies have been added to the New Zealand network (Figure 7.1 and Figure 7.2).

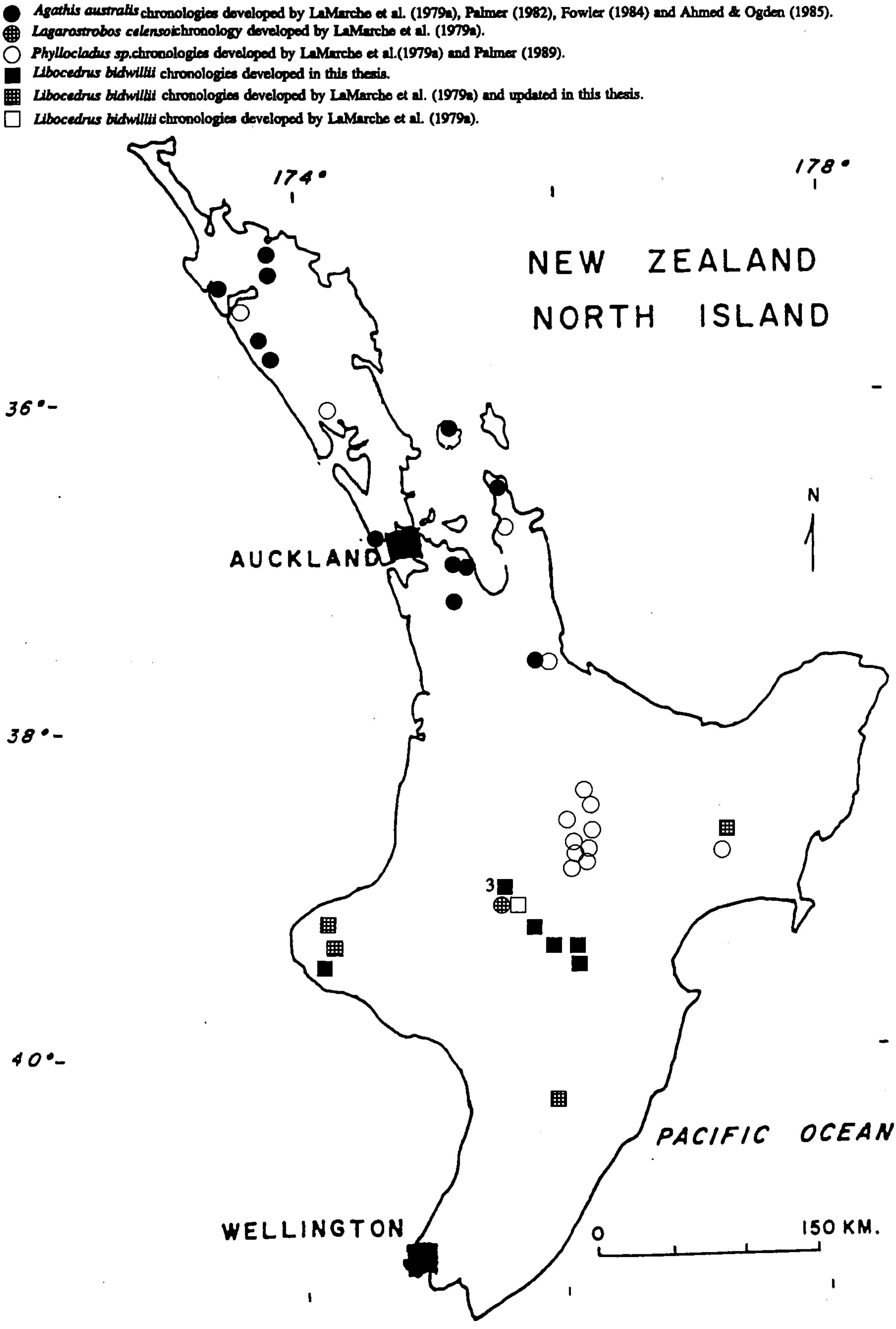


Figure 7.1 Locations of tree-ring chronology sites in North Island, New Zealand. At several sites more than one chronology has been developed.

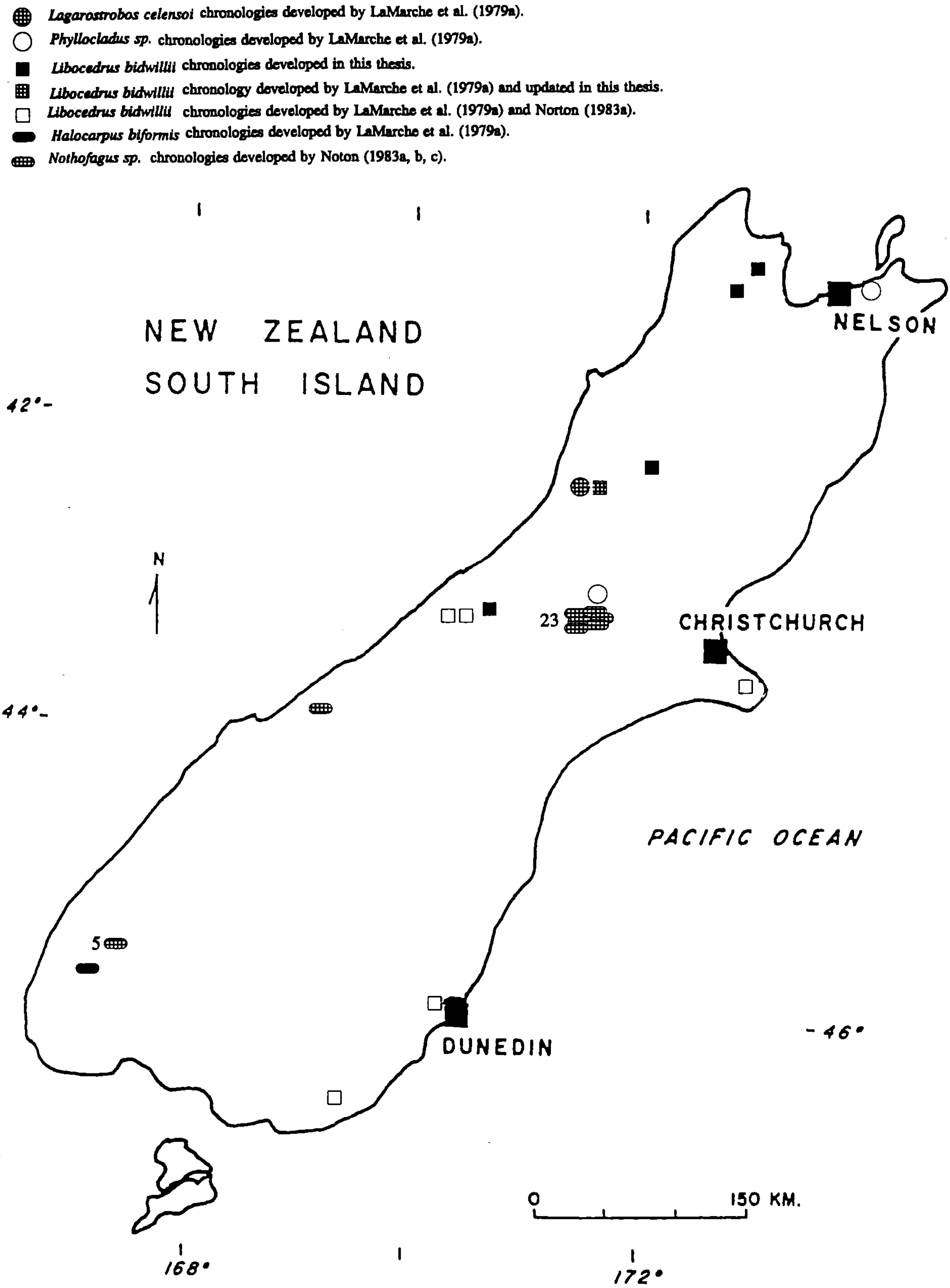


Figure 7.2 Locations of tree-ring chronology sites in South Island, New Zealand. At several sites more than one chronology has been developed.

A survey of the climate quality of the chronologies was undertaken through the use of response function analyses. This is the first time the use of the bootstrap response function and transfer function have been applied to New Zealand species. The bootstrap function proved to be a very useful tool in a country with relatively short climate records.

A major contribution of this work has been the reconstructed climate data. The reconstruction was based on two groups of chronologies: one was the 11 nation-wide chronologies; the other was the three longest chronologies. The reconstruction produced from the three longest chronologies was the first high resolution climate data series to extend back 500 years in New Zealand. The output of this work was also the first successful nation-wide precipitation reconstruction. Speleothems (secondary minerals in caves such as stalagmites and flowstones) and tree-rings can both yield palaeo-temperature and water balance data. The output of this thesis has proved that these independent sources of information can be used to validate each other. The data sources are also complementary, with tree-rings providing annual resolution data for several centuries and speleothems yielding lower resolution data extending over many millenia.

7.2 Summary of thesis chapters

This section summarises the main contents and highlights some specific points of interest raised in the previous chapters.

7.2.1 Chapter one

This chapter gave a historical review of dendrochronology and dendroclimatology in Australia and New Zealand, and reviewed the research on *Libocedrus bidwillii*. Following this was an outline of the aims and scope of the thesis.

Tree-ring data are one of the most accurate sources of proxy climate information. Eighteen chronologies have already been established in Australia, most of them from Tasmania. The longest published chronology was developed from *Lagarostrobus* *franklinii* in Tasmania extends from AD 900 to 1988 (Cook *et al.* 1991). There have been 4 temperature and 8 riverflow data series reconstructed from tree-ring chronologies in Australia. In New Zealand, there were 72 chronologies produced from tree-rings. The longest was from *Libocedrus bidwillii* which covered the period from AD 1256 to 1976. There were 3 temperature, 1 precipitation, 1 riverflow and 1 pressure reconstructions from different tree-ring chronologies.

One of the things this chapter highlighted was the limited scope for dendroclimatic reconstruction from Australia; the only really comprehensive network of chronologies have come from Tasmania. On the other hand, New Zealand has had a rapid development of over 70 chronologies but with relatively few reconstructions; the most notable thing has been the virtual absence of precipitation and river flow reconstructions from New Zealand [Norton's rainfall reconstruction (Norton, 1987) was only back to 1879 for Canterbury region].

Libocedrus bidwillii is widely distributed throughout New Zealand. It reaches an old age, has clear annual-rings and large year to year ring width variation. Eleven successful chronologies had already been developed from this species, but so far no climate reconstructions had been attempted. It was important to: (1) determine if this species was sensitive to climate not only from a statistical viewpoint, but also physiologically; (2) extend both spatially and temporally the network of chronology sites as far as possible. This provided a better basis for climate reconstruction.

7.2.2 Chapter two

The focus of chapter 2 was to determine the linkages between annual ring growth and climate by investigating seedling growth in response to varying temperatures and soil moisture.

The experiment ran for a year and half and showed that seedlings of *Libocedrus bidwillii* were sensitive to temperature and soil moisture. The greatest growth was at high soil moisture and under a variable temperature regime. There was obvious seasonal variation in the growth of the seedlings. Growth started in spring, was highest in summer and nearly stopped in winter. It is unfortunate that the dendroband experiment carried out in the field was not successful due to equipment failure and problems with the site (refer to Appendix 1). However, the dendrobands showed some general growth patterns and relationships with the environment in adult trees. Those two experiments confirmed the annual nature of the rings and the possibility of climate reconstruction from this species.

7.2.3 Chapter three

This chapter discussed the development of chronologies from 23 sites. Twelve new sites, 5 updated sites and 6 non-updated sites were included. The longest chronologies in New Zealand now extend from AD 1140 to 1992 (site UWR) and from AD 1256 to 1992 (site TKP).

The quality of cross-dating was verified using the COFECHA program. All the cores included in the final chronologies were highly correlated with each other.

The standardisation approach was aimed at maximising the climate signal in the series. Towards this a double detrending method of standardisation was employed. The chronologies developed from different double detrending methods showed that there were very similar signals at the high frequency bands but very different signals at low frequency. Only the ERH+SP67% (linear-Exponential or linear Regression or a Horizontal detrending plus SPline detrending using 67%n criterion) method kept the signals which were longer than 120 years. The results from spectral analysis of climate data showed some low frequency signals which were longer than 120 years. In order to keep more climate information in the chronology, ERH+SP67% method was selected as the final standardisation method although this lead to some reduction of EPS and SNR. Autocorrelation in the chronologies was removed by ARSTAN program with AIC to choose the model. No significant autocorrelations were left in the residual chronologies produced by this method.

In the conclusions to Chapter 3, it was stressed that the choice of a standardisation method must be done with the research objectives in mind. If the aim is to retain the maximum amount of low frequency trend present in ring measurement series, then a spline filter may not be the best choice. Only strict linear, negative exponential, or even horizontal lines through the mean may be enough. If the low frequency is due to processes not related to climate, and climate is the desired signal, then these trends should be removed. How do you determine whether low frequency trends are due to non-climatic factors ? The only answer seems to be know the data and the site. It was considered unwise to use standardisation methods as a “black box”.

7.2.4 Chapter four

This chapter examined the relationships between chronologies.

The chronologies showed highly consistent and significantly correlated patterns between nearly all of the sites. A relationship exists between inter-chronology correlations and separation distance. A simple linear regression could be applied to the relationship between the correlation coefficient and the difference of altitude. There was significant linear relationship between the correlation coefficient and log transformed separation distance. The spectral and coherence analysis showed that there were similar cycles when the sites were closer.

A principal component analysis of the 23 chronologies showed that about 85 per cent of the total variance was explained by 10 components with the first three explaining 62 per cent. The component patterns were complex and several chronologies had anomalous loadings. The first three components were shown as figures and discussed.

An interesting find was that chronologies of *Libocedrus bidwillii* may be different if different sized (aged) trees were included in the chronology from the same site. A conclusion was that a chronology from one site should include different sized trees if possible.

7.2.5 Chapter five

This chapter discussed the relationships between chronologies and climate variables. The implementation details of the response function used in this thesis were described in detail.

Based on verification results and binomial distribution tests, 27 pairs of response functions were significant out of a possible 69. A summary of the response functions was produced incorporating only significant coefficients from the individual analyses. In general the response functions showed a negative relationship between temperature for the prior growth months February, March and current December, while there was a positive response to temperature in September and February. There were three significant negative coefficients (previous March, April and August) and one positive (current February) for precipitation.

A principal component analysis (PCA) of the response function coefficients was carried out and discussed in relation to the PCA of the actual chronologies. PCA results showed that all the 27 significant response function analyses could be formed into four groups. The response functions for the new climate data-base and combined chronology of the four groups showed that three of the four response functions were significant with independent verification. Temperature had a similar response pattern in the four groups but the rainfall response was more variable. A simple discussion on Kalman filters was also included in this chapter.

7.2.6 Chapter six

The PVP criterion devised by Guiot (1982) for removing nonsignificant predictors was shown very valuable. PVP selection of the PCA analysis resulted in more than 90% of variance retained and 1/2 to 1/3 of the variables reduced. Group A chronologies, the three longest chronologies from Group A and Group B chronologies were selected to reconstruct past climate.

Correlation and response function analyses using different climate variables with site and regionally averaged chronologies were used to indicate possible variables for reconstructions. Average February-March temperature and total March-April precipitation were finally selected as the reconstruction variables based on the independent verification results.

The temperature reconstruction from Group A was better than that of the three longest chronologies even though both transfer functions were significant. The reconstruction from the three longest chronologies was further discussed because it was the only data series to extends back 500 years in New Zealand. The reconstructed temperature series was highly correlated with other reconstructions from tree-rings. It also agrees well with iceberg, glacial evidence, isotope evidence from tree ring data and speleothem palaeotemperature curve evidence.

In the precipitation reconstruction, Group A reconstructed more extreme years than did the three longest chronologies. However, the reconstruction from the three longest chronologies had a higher match ratio with observed data than that of Group A. The reconstructed precipitation had a similar pattern with the other limited sources such as Rotorua closed basin lake levels and varying rates of changes of streambeds in Hawkes Bay.

It was stressed in the discussion of the results that in the general transfer function, there was a large difference in the correlation coefficient and RE (reduction of error) value depending on which period was used for calibration. This often leads to under or over estimations. The bootstrap method solved this problem because it was calibrated over a longer period while still having independent verification.

7.3 Suggestions for future research

It was an unavoidable conclusion that to some extent the geographical spread was limited and that the early statistical quality of many of the currently available *Libocedrus bidwillii* chronologies in New Zealand remains poor. This was because of the relatively small number of older samples in these chronologies. Further fieldwork is needed to improve this. A future sampling strategy for *Libocedrus bidwillii* should bear in mind that some older samples are needed to improve the early statistical quality. At the same time, some relatively young samples are needed because of the possibility of poor climate response by older trees.

The work reported in this thesis was concerned only with one species - *Libocedrus bidwillii*. The incorporation of different species should widen climate sensitivity.

Eighty-four tree-ring chronologies have been developed from several species in New Zealand now (Figures 7.1 & 7.2). These provide the potential for an excellent data base for palaeoclimaic studies. However many of the chronologies were only dated visually and substantial quantities of older material were omitted because they could not be easily cross-dated. Developments in dendrochronology over the last decade, particularly in the fields of computer cross-dating and standardisation, have greatly enhanced the ability to accurately date tree-ring chronologies and to derive consistent standardised time series. The existing chronologies need to be quality control screened, reanalysed (cross-dating, standardisation) where appropriate and prepared into a consistent format.

Maximum and minimum wood densities, and the proportion of latewood to earlywood, are parameters known to reflect climate conditions in Northern Hemisphere studies (Hughes *et al.* 1984). None of this kind of work has be tried in New Zealand. There is great potential to include these kinds of variables in future research.

The extension of both time and space of chronologies should improve the chances of better climate reconstructions. Future work to increase the network in New Zealand should be particularly valuable for spatial reconstruction. Attention should be given to maintaining a good East/West, North/South and High altitude/Low altitude distribution of sites. Empirical experimentation with different seasonal and integrated climate parameters should continue but attention should be given to the results of phenological and ecological work which might give a better understanding or help the interpretation of the climate signals in chronologies.

For the methodology of reconstruction, statistical improvements should continue to be sought. Attention should be given to the fact of that the relationships between tree growth and climate might alter with time. For example, increasing levels of atmospheric pollution or carbon dioxide may have changed the relationship between trees and climate factors in the last few decades. This means that techniques such as the Kalman filter should be used to investigate more species responses.

A priority research need has been identified in the September 1994 Report of the National Science Strategy Committee for Climate Change, namely the provision of "improved quantification of palaeoclimate changes as a basis for testing regional climate models" (New Zealand climate change programme, 1994). A recent Workshop convened by the Royal Society of New Zealand (1994) on 'Palaeoclimates and Climate Modelling' revealed that, while considerable knowledge exists on palaeoclimates in New Zealand, very little is in the quantitative form that is needed for understanding the present limits of climate variability and for validating hindcast regional climatic models. In conclusion of this research programme, it must be stressed that more extensive and better quality ring-width and other dendrochronological data (such as wood density data) are required in New Zealand. Many problems and many possibilities for experimentation with statistical methods still exist. It is hoped that the work described in this thesis will be of benefit to the climate change research in New Zealand, and, ultimately, around the world.

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APPENDICES

APPENDIX ONE

SEASONAL AND DAILY RADIAL GROWTH FLUCTUATION - AN ELECTRIC DENDROBAND STUDY*

1 Introduction

A great deal of work has been carried out on the cambial growth of mature trees, particularly in relation to rainfall and hydration changes (Kozlowski, 1967). In most studies measurements of diameter were made at widely spaced intervals of time, making the precise observation of radial changes impossible (Green, 1969). Fritts and Fritts (1955) made a dendrograph capable of accurately recording changes in radius as small as 0.0025 mm. This instrument was suitable for observing radial changes in slow-growing hardwoods and was used in several studies of radial growth in relation to environmental variation in trees (Fritts, 1958) and in young seedlings (Kozlowski, 1967).

In recent years, dataloggers have been used in a number of different fields, such as industry, security systems and automotive diagnosis, as well as environmental or meteorological data monitoring. The use of automatic dataloggers to monitor environmental conditions in forest research has also become increasingly common throughout the world (Brand *et al.*, 1988). However, no datalogger system and electric dendroband study has been reported from indigenous New Zealand tree species in their natural environment. The only reported study in which band type dendrometers, measuring circumferential changes, have been used to study the growth of indigenous NZ trees in natural environments are those of Benecke & Havranek (1980) on *Nothofagus solandri var. cliiffortiioides* and Palmer & Ogden (1983) on *Agathis australis*.

* References cited in this Appendix are included in the main reference list of the thesis.

The objective of this research was to provide biological data to assist with setting up and interpreting response function analyses of the dendroclimatic study of *Libocedrus bidwillii.* A datalogger system was installed on site RUH (Rahu Saddle, 672 metre high above sea level) located at 42°18.95'S, 172°07'E; about 250 kilometres west of Christchurch, South Island, New Zealand. The major trees are *Libocedrus bidwillii* and *Nothofagus solandri* var. *cliiffortiioides* and less abundant *Nothofagus menziesii.* Veblen & Stewart (1982) have studied the population structure of *Libocedrus bidwillii* at this site. LaMarche *et al.* (1979a) cored some trees from this site but they failed to crossdate. Another 25 trees (47 cores) were cored from this site and successfully cross-dated to construct a chronology from A.D. 1560 to 1991 (refer to site RUH in Chapter 3).

2 Methods

Two electric dendrometer bands were used for this research. The bands are electronic transducers (Rubbery Ruler transducers) manufactured by the School of Physics, University of Melbourne, Australia. The data recorded from the bands were frequency. The calibration was done by manufacturers and the two bands have separate calibrations (Cimmino, *pers. comm.*). The bands were assembled in the field on 9 October 1992 and taken off on 10 October 1994. Concerns about resin flowing down the trunk causing the band to stick were overcome by placing a strip of polythene sheet between the trunk and the upper edge to fold over the band (Palmer & Ogden, 1983). Two trees were banded and 2 increment cores were taken from each tree when it was banded. These cores were mounted, surfaced, and used to determine mean radial growth rates. At the end of the study period, 2 more cores were taken from each tree.

Temperature sensors and moisture sensors were also set up at the same time. Three sub-sites were used to install sensors to measure temperature and moisture in the soil at 5 cm and 15 cm depths. Another two temperature sensors were installed on a tree to measure air temperature. A rainfall gauge and light sensor were also installed. A battery and solar panel were used to supply the energy for the datalogger.

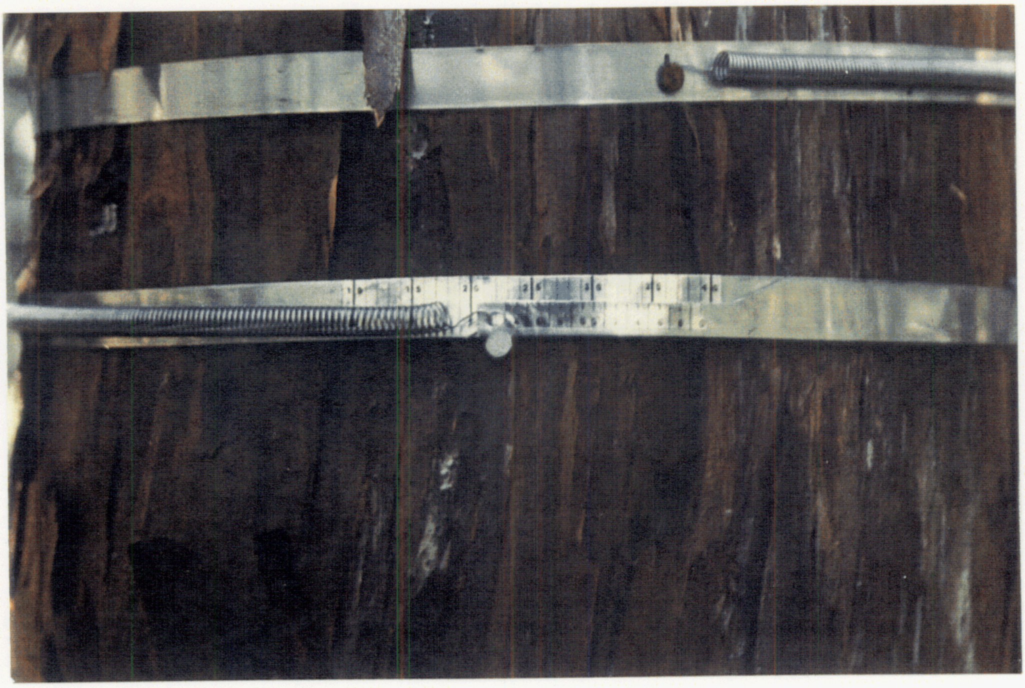

Figure 1 A general dendrometer band placed on a *Libocedrus bidwillii* tree at the Rahu Saddle site (RUH).

Figure 2 An electric dendrometer band placed on a *Libocedrus bidwillii* tree at site RUH.

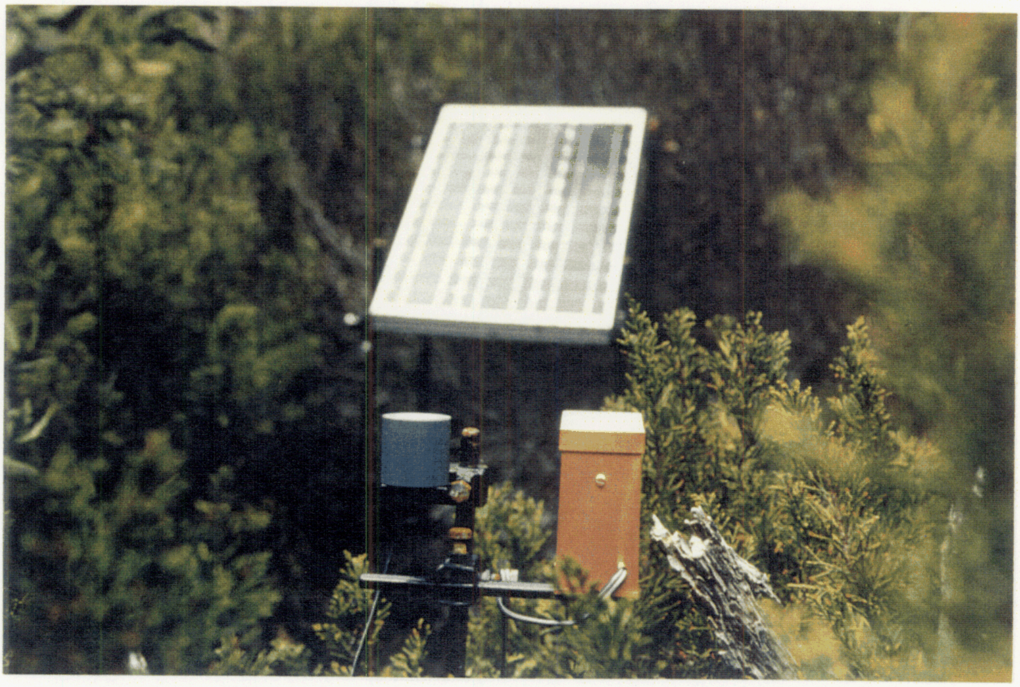

Figure 3 A rainfall gauge, light sensor and solar panel were installed at site RUH.

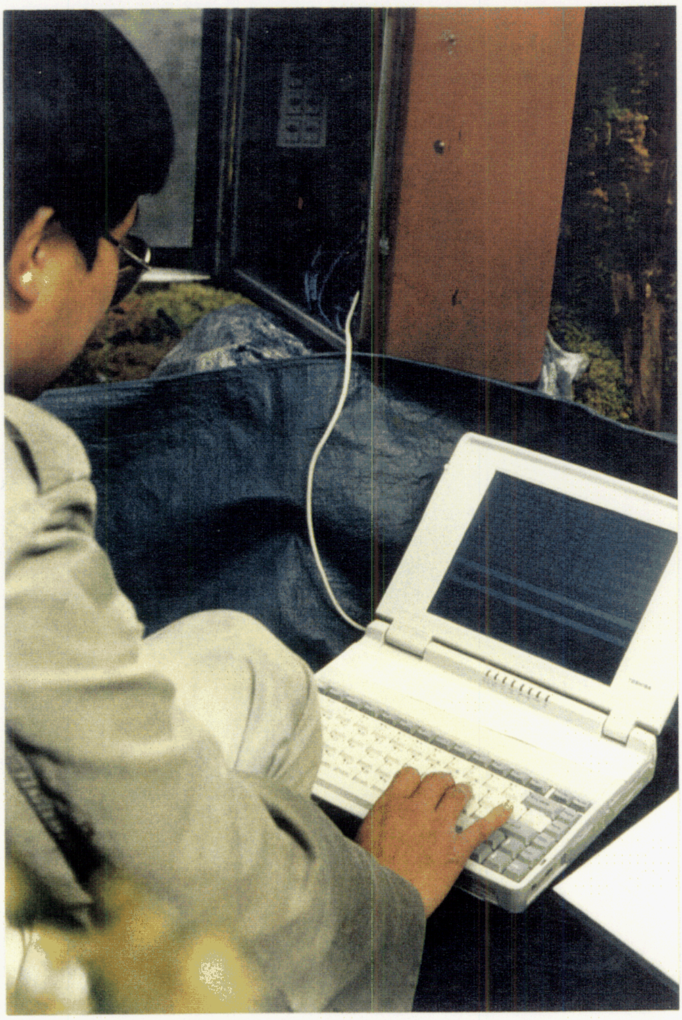

Figure 4 Downloading data from datalogger to computer.

All the bands and sensors were connected to a datalogger which contained a memory card. The datalogger was set-up to record once every four hours (this value was the average from the previous 4 hours). The recorded data were downloaded every three to five months mainly to check the equipment rather than concerns about the lack of memory. Lightning damaged the datalogger in January 1994 and was taken back to Lincoln University and repaired. As a result, about 20 days of data was lost.

Apart from the pair of electric dendrobands, some simple dendrometer bands were also installed on several other trees in this site in order to provide more data.

Measurements by electric dendrometer bands include stem swelling caused by moisture changes in the bark and xylem as well as increases due to cambial activity and cell expansion (Fritts *et al.* 1965). The coring at the end of the experiment was done to check out the possibility that the recorded measurements simple reflected stem shrinkage and swelling rather than changes in growth rate (Palmer & Ogden, 1983).

3 Results

The growth rates determined from increment cores of 10 different sites are given in Table 1. The mean growth rate of site RUH is slightly below most of other 9 sites.

Table 1 Radial growth of *Libocedrus bidwillii* at 10 different sites*

Chronology sites	EMT	TOA	TKP	RUC	UWR	MOA	OKA	WBA	ARM	**RUH**
No. of trees/cores	22/66	25/43	37/63	29/73	38/68	20/49	14/47	15/31	22/46	**20/40**
Chronology span	375	483	737	519	853	502	245	319	513	**433**
Mean ring width (mm)	0.98	0.60	0.66	0.71	0.56	0.47	0.90	0.98	0.81	**0.52**
Standard deviation (mm)	0.391	0.249	0.309	0.282	0.267	0.228	0.180	0.374	0.327	**0.285**

* Refer to chapter 3 and appendix 2 for detailed description of each site.

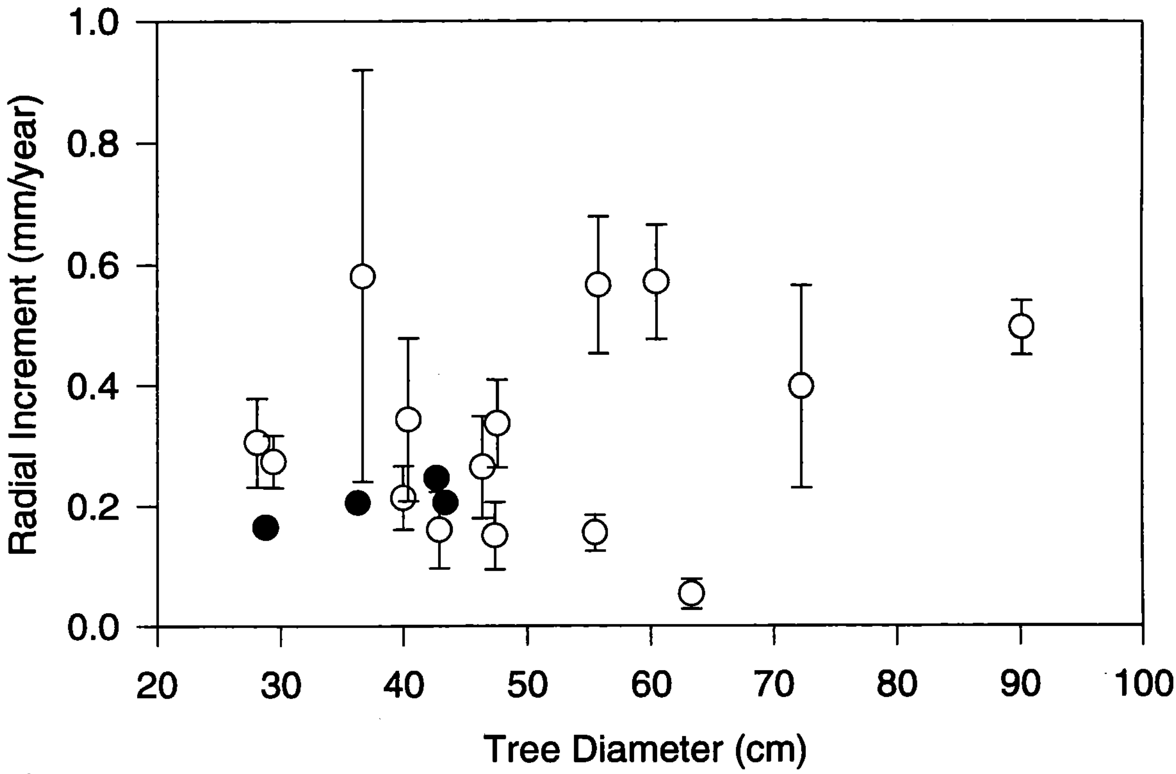

Figure 5 Comparison of radial increment from the general dendrometer bands with measurements from 2 cores per tree in site RUH.

● Radial increment measured from general bands (1993-1994).

○ Average annual radial increment and their standard deviation from 1980 to 1991.

Figure 1 shows the relationship between radial increment and DBH (diameter at breast height) at site RUH since 1980. The radial increment from simple dendrometer bands was also shown in this figure.

The relationship between seasonal radial fluctuation and environmental factors are shown in Figure 2. An increase in radius was only really obvious as a persistent trend after September 1994 (possibly due to a long period of "bedding in" of the bands) (Palmer & Ogden, 1983). Consequently, the 12 month-span, from September 1993 to September 1994 (January 1994 was missed due to equipment failure), was picked for further analysis. Table 2 gives the simple correlation coefficients for July (because the radial increment values in July were obviously higher than other months) and the twelve month span.

Table 2 The simple correlation between tree growth and environmental factors

Tree	T5	T15	T-air	M5	M15	Rain.	Light
July 1993 and July 1994 (number of observation = 326)							
RUH8	-.0358[1]	-.0131	-.0792	-.0181	-.0212	0.0512	-.1248
	0.5196[2]	0.8136	0.1536	0.7453	0.7033	0.3571	0.0242
RUH9	-.0506	-.0293	-.0058	-.0542	-.0323	0.0638	0.0522
	0.3623	0.5978	0.9176	0.3290	0.5617	0.2506	0.3472
Sept. 1993 - Sept. 1994 (number of observation = 1995)							
RUH8	0.0199	0.0253	-.0409	0.0039	0.0011	0.0289	-.1238
	0.3752	0.2579	0.0679	0.8630	0.9593	0.1977	0.0001
RUH9	0.0527	0.0628	-.0297	0.0068	0.0097	0.0615	-.0822
	0.0185	0.0050	0.1842	0.7616	0.6644	0.0060	0.0002

Note:

1. Correlation coefficient.
2. Probability that the value could occur by chance.

T5, T15 refer to soil temperatures at 5 & 15 cm depth respectively; T-air is air temperature; M5 & M15 refer to soil moisture at 5 & 15 depth respectively; Rain is total rainfall; Light is light intensity measured by the light sensors (with higher value at night).

The results of stepwise multiple regression was shown in Table 3. In order to discuss the daily fluctuation in detail, the average of the four hour records for three months was picked from the active growth season (October - March) and shown in Figure 3.

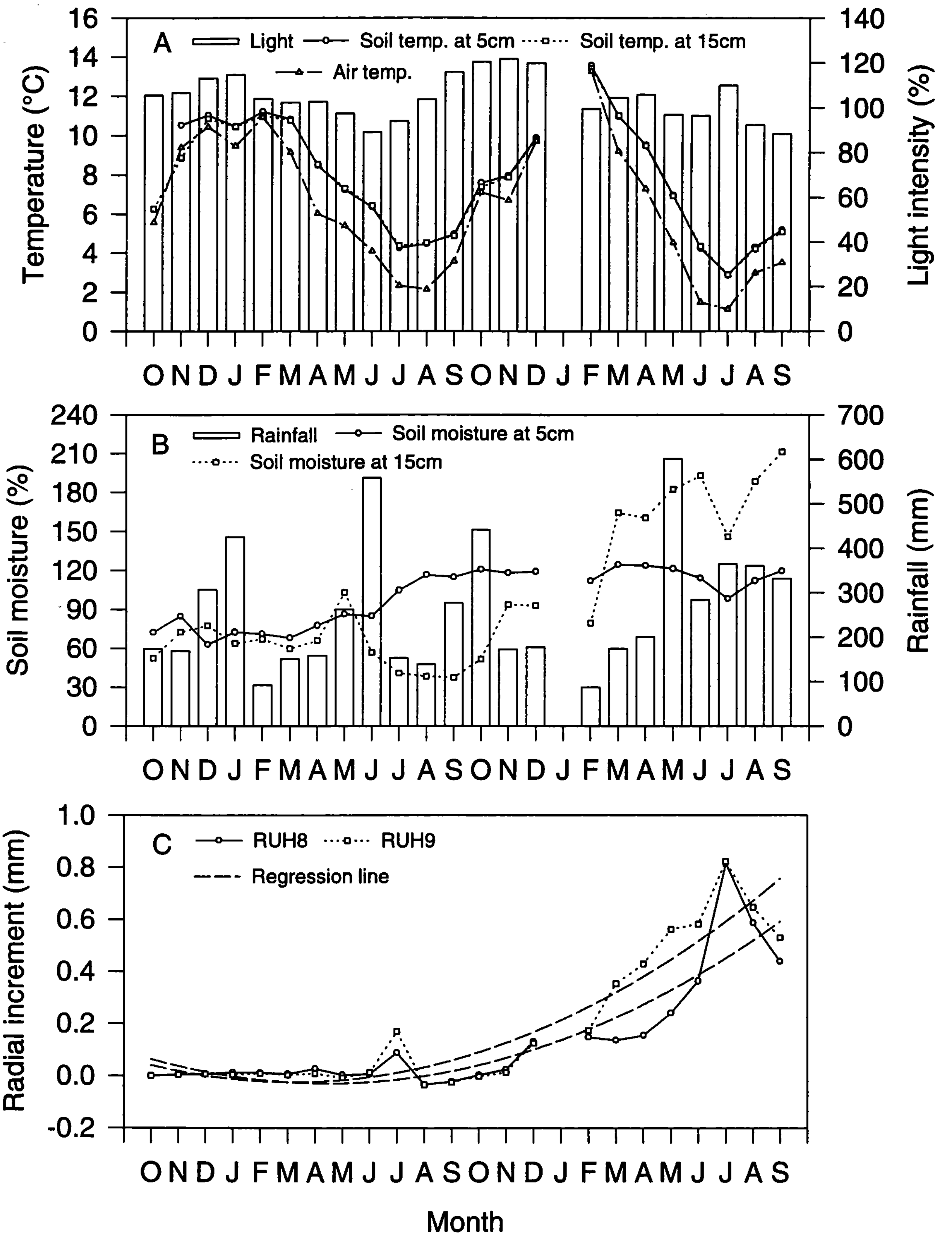

Figure 6 Environmental data and tree increment recorded by a datalogger from October 1992 to Sept. 1994. Light intensity and soil moisture are the percentage of the average of the whole experiment period.

Table 3 Summary of the significant ($p < 0.05$) stepwise multiple regression functions.

Month	T5	T15	T-air	M5	M15	Rain	Light	Σ+	Σ-	Σ±
Tree RUH8 (DBH = 47.6cm)										
Sept. 93								0	0	0
Oct. 93			+					1	0	1
Nov. 93	-							0	1	1
Dec. 93	+							1	0	1
Feb. 94							-	0	1	1
Mar. 94	-	+			+	+		3	1	4
Apr. 94							-	0	1	1
May. 94							-	0	1	1
Jun. 94								0	0	0
Jul. 94							-	0	1	1
Aug. 94							-	0	1	1
Sept. 94							-	0	1	1
Σ+	1	1	1	0	1	1	0			
Σ-	2	0	0	0	0	0	6			
Σ±	3	1	1	0	1	1	6	5	8	13
Tree RUH9 (DBH = 28.1cm)										
Sept. 93								0	0	0
Oct. 93			+				-	1	1	2
Nov. 93								0	0	0
Dec. 93	+	-	-				+	2	2	4
Feb. 94						+	-	1	1	2
Mar. 94	-	+	-		+	+		3	2	5
Apr. 94							-	0	1	1
May 94						+		1	0	1
Jun. 94								0	0	0
Jul. 94								0	0	0
Aug. 94								0	0	0
Sept. 94								0	0	0
Σ+	1	1	1	0	1	3	1			
Σ-	1	1	2	0	0	0	3			
Σ±	2	2	3	0	1	3	4	8	7	15

Note: refer to table 2 for the explanation of T5, T15, T-air, M5, M15, Rain & Light.

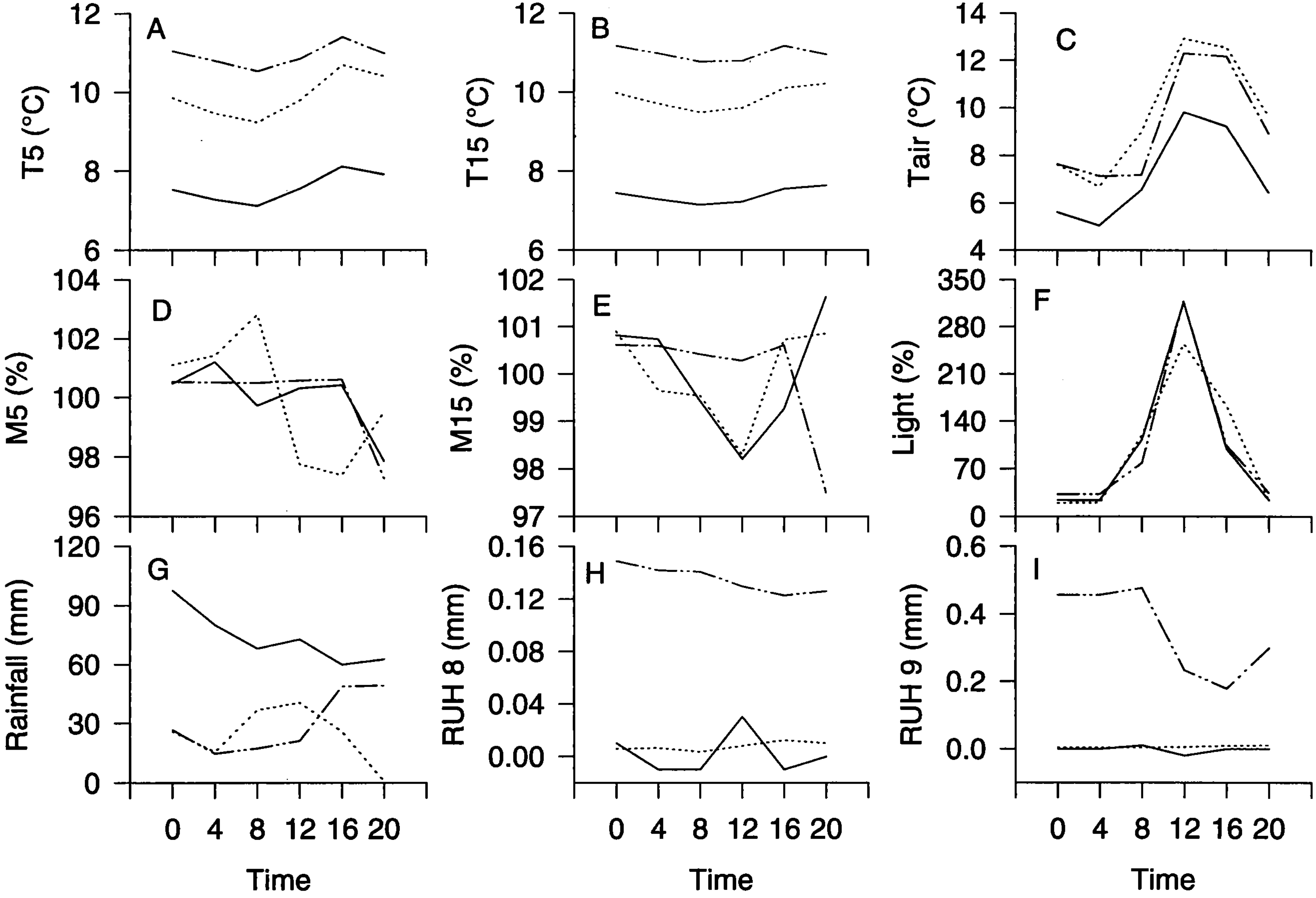

Figure 7 Daily variation recorded by the datalogger in October 1993, December 1993 and March 1994. Soil moisture and light intensity are the percentage of the average of the whole experiment period. —— Average of October 1993 ········ Average of December 1993 —··— Average of March 1994. Refer to Table 2 for the explanation of T5, T15, T-air, M5, M15.

4 Discussion

4.1 Measurements

The temperature sensors and rainfall gauge calibrated closely with observed data in the laboratory. The quality of soil moisture results were disappointing and were considered not good enough to reflect the real situation. The light sensors recorded the high intensity as low values and low intensity as high values, this was transformed inversely and calculated as a percentage of the average of the whole periods.

The results obtained by using the electric dendrobands accurately reflected the radial increment associated with the formation of an annual ring. The radial increments measured from electric dendrobands from Sept. 1993 to August 1994 were 0.4 mm (RUH8) and 0.5 mm (RUH9). This is very similar to the results obtained from the increment cores. The measurements from the simple dendrometers were slightly smaller than the above measurements (Figure 1). This may indicate an initial period of 'taking up the slack' before the bands registered growth (Palmer & Ogden, 1983). The electric bands seem to take one year (Oct. 1992 to Sept. 1993) before starting to record growth (Figure 2). Because the simple dendrometers were installed one year after the electric ones, it is perhaps no surprise that they recorded a smaller value than the electric bands in the 1993-1994 growth year.

4.2 Seasonal fluctuation

'Apparent growth' or net increment was recorded during most months of the year (except for the “bedding-in” period, Figure 2). Maximum increment occurred during the summer and autumn months. During June and August, increment of growth ceased. The obvious abnormal result is that the recorded increments from July of 1993 and 1994 were higher than all other months. Table 2 shows that the July tree growth measurements were negatively correlated with most of the environmental factors except rainfall in both trees and light in RUH 9. Light in RUH 8 was the only significant coefficients. Most of the correlation coefficients from the whole year's data are positive except for air temperature and light intensity. This means that lower temperatures and light intensity will contribute to a higher measurement to the record which may not be related to growth.

July had the lowest air temperature but highest tree increment records. This result is unable to be explained in terms of a biological growth response. Consequently, the manufacturer was contacted referring the equipment.

The temperature dependence of the rubbery ruler (RR) transducers is mainly due to the timer chip (Cimmino, *pers. comm.*). This is of the order of 50 ppm/°C according to manufacturer's specifications. Assuming a worst case of 100 ppm/°C, this would correspond to a shift in frequency of 0.1% over the 10/°C temperature excursion between summer and winter. From Figure 2, it is impossible to decide wether this sort of drift can account for the July data. If the abnormality is due to thermal drifts, then the same sort of variation should appear in the daily data due to the difference between day and night temperatures. It should then be very easy to remove thermal drifts from the seasonal data since the contribution to variation in output frequency due to daily growth can be neglected. But the daily data (Figure 3) cannot account for the apparently abnormal growth pattern (some months have day/night variation, some have not). Other researchers use the RR to monitor the swelling of trees in catchment areas as function of rainfall. Other still use RR to monitor the growth of fruit as function of irrigation (such as orange growth). Figure 2 shows some correlation with rainfall during the abnormal growth period. It is quite possible that at least part of the apparent growth in the dormant period is in fact due to (delayed) swelling of the trunk due to increase in soil moisture (Cimmino, *pers. comm.*) These need to be further studied in the future.

The results of stepwise multiple regression analysis (Table 3) show that tree growth was significantly related to most of the environmental factors from October to March. These results suggest that the summer climate was closely correlated to tree growth. The exception was rainfall in May for RUH 9 and light intensity for both trees in the winter period. Light intensity had a negative significant coefficient in the winter period for RUH8 and no explanation is known for this.

4.3 Daily variation

Three months for the active growth season (Oct. - Mar.) were selected to discuss in more detail. Figure 3 shows the daily average of these three months. Soil temperature has the lowest value at 8 am and highest value at 4 pm (Figure 3A & B). Air temperature reached lowest point at 4 am and highest point at 12 pm (Figure 3C). The soil temperature in March was highest and October was the lowest. Air temperature in December was the highest and October was the lowest. Air temperature was the most variable and soil temperature at 15 cm was the most constant. Daily light variation did not change much in all the three months (Figure 3F). October had the higher total rainfall compared with that of December and March. There was more rain in the morning (0 am - 8 am) in October, during the day time (8 am - 4 pm) in December and the afternoon (12 pm - 8 pm) in March (Figure 3G). The recorded tree fluctuations are different in the two trees. The smaller tree (RUH 9) is more variable during the day, especially in March. Both of the trees have a higher values in the morning and lower values in the afternoon, this is a similar pattern to that of soil moisture and reverse pattern to that of the air temperature. Such anomalies are difficult to explain and raise questions about the whole data-set and bands in particular.

5 Conclusions

1. The results obtained by using electric dendrobands accurately reflected the overall, annual radial increment. The electric bands seemed to take nearly one year to start recording growth (i. e. taking up the slack).

2. Tree growth was significantly related to most of the environmental factors from October to March. These suggested that the summer environmental factors contributed most to the tree growth.

3. The obvious abnormal high growth value in July is unable to be explained.

4. Both of the banded trees had higher increment values in the morning and lower values in the afternoon, this is a similar pattern to the daily soil moisture and the reverse pattern of daily air temperature.

APPENDIX TWO

SITE INFORMATION AND CHRONOLOGY LIST*

Site and collection information (AHA)

Site name: Ahaura **Site abbr.:** AHA
Country: New Zealand **State or Province:** South Island
Latitude: 42°23'S **Longitude:** 171°48'E **Altitude:** 244m
Species collected: *Libocedrus bidwillii*
Date of original collection: 27 December 1977
Original collectors: P. W. Dunwiddie, M. R. Boase
No. of trees/cores sampled (original): 15/58 **No. of discs:** 1
Date of new collection: 8 December 1993
New collectors: L. Xiong; J. G. Palmer; B. E. Smith
No. of trees/cores sampled (new): 21/43 **No. of discs:** 0

Site description:

LaMarche *et al.* (1979a) described the site as followings:

Two species, *Dacrydium colensoi* and *Libocedrus bidwillii*, were collected at the Ahaura site located in western South Island. The trees are fairly common in the area, but occurrence is very scattered in the gently rolling, boggy countryside. Both species are emergent (12-15 m tall) from a 6-8 m scrub of *Phyllocladus alpinus, Nothofaqus solandri var solandri*, and *Leptospermum scoparium*. *Libocedrus* regeneration is abundant in the very open forest.

The site is reached by following Orwell Creek road east 22 km from Ahaura, then turning left at all intersections for 8 km. Relocation of exact trees is probably impossible; numerous gravel roads bisect this area, and trees were cored along a 0.5 km stretch of road with no notable landmarks. No stumps from logging or other signs of disturbance were found, although the open character of the forest suggests a possible fire at some time in the past. A single disc of *L. bidwillii*, cut near Clark's River, was obtained from a local sawmill.

The site was resampled in 1993. The bridge at about 4 km from Orwell Creek has been broken the last few years. The site has been extensively disturbed (i.e. milled) in recent years. We were unable to locate the exact original trees.

Summary of chronology statistics:

Chronology 1525 to 1992 (468 years) 32 trees 59 radii

Chronology type	STNDRD	RESID (AR 2)	ARSTAN
Mean	1.0000	1.0049	1.0006
Median	1.0013	1.0009	.9988
Mean sensitivity	.1371	.1556	.1325
Standard deviation	.2097	.1396	.2099
Skewness	-.0235	-.1242	.0049
Kurtosis	.4968	.9025	.4666
Autocorrelation order 1	.6535	-.0050	.6714
Partial autocorr order 2	-.0429	-.0060	-.1024
Partial autocorr order 3	.0140	-.0652	-.0432
Variance due to autoregression	41.3%		43.8%
Error variance	.006324		.004955
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.7834

* Refrences cited in this appendix are included in the main reference list of the thesis.

Common interval 1774 to 1963 (190 years)	Detrended series	Residuals (white noise)	19 trees	32 radii
Mean correlations:				
Among all radii	.265	.304		
Between trees (Y variance)	.252	.294		
Within trees	.657	.590		
Signal-to-noise ratio	6.405	7.914		
Agreement with population chron	.865	.888		
Variance in first eigenvector	32.84%	33.76%		
Chron common interval mean	1.016	1.004		
Chron common interval std dev	.194	.134		

Chronology listings

Residual Chronology of AHA:

	Tree-Ring Indices										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1530	1270	893	1282	756	1122	861	1059	809	1388	1097	1	1	1	1	1	1	1	1	1	1
1540	738	1496	1191	1061	862	1275	691	1019	780	1013	1	1	1	1	1	1	1	1	1	1
1550	811	926	1292	842	779	891	975	959	760	820	1	1	1	1	1	1	1	1	1	1
1560	872	600	1143	728	1632	1274	755	1336	1124	1006	1	1	1	1	1	1	1	1	1	1
1570	395	676	776	943	1000	683	902	904	943	769	1	1	1	1	1	2	2	2	2	2
1580	1045	839	804	1111	974	824	1160	1143	862	1175	2	2	2	2	2	3	3	3	3	3
1590	974	1035	999	1034	960	802	1179	984	849	927	5	5	5	5	5	5	5	5	5	5
1600	1140	988	1009	1154	1361	1312	820	1129	741	1110	6	6	7	8	8	8	9	10	10	10
1610	821	876	1219	978	989	909	841	879	923	896	10	10	10	10	10	10	10	11	11	11
1620	975	1054	930	1038	1155	868	839	1148	1393	1077	11	11	11	11	11	11	11	12	13	13
1630	947	954	1018	794	1023	987	1149	737	860	1136	13	14	14	14	14	14	14	14	14	14
1640	1274	1020	1030	975	1126	1128	949	972	883	950	14	14	14	14	14	14	15	15	15	16
1650	1047	1392	810	1205	1030	966	1019	1004	1062	987	16	16	16	16	16	16	16	16	16	16
1660	995	968	813	896	1084	946	927	817	1196	893	16	16	17	17	17	17	18	18	18	18
1670	1147	1241	1151	1077	1100	894	967	1095	1042	890	18	18	18	18	18	18	18	18	18	19
1680	1111	1203	818	1026	989	1108	834	1049	1416	1103	20	21	21	21	21	21	21	21	21	21
1690	1037	686	1107	1002	1146	1202	871	867	921	878	21	21	21	21	21	21	21	21	23	23
1700	919	1028	893	933	981	847	1071	805	1046	1186	23	24	24	24	24	24	24	25	25	25
1710	897	1196	819	873	1233	1160	1161	1019	820	1268	25	27	29	29	29	29	30	30	30	31
1720	912	980	943	1154	979	994	969	1007	1053	703	31	31	31	31	31	31	33	34	34	34
1730	1061	754	896	1073	1093	1017	985	884	934	1260	34	34	35	35	35	35	35	35	36	36
1740	947	777	1083	947	959	1187	1059	947	1185	948	37	37	37	37	37	37	37	37	37	37
1750	962	1137	792	965	963	993	987	856	941	982	37	37	37	37	38	38	38	39	39	39
1760	1129	962	1158	1252	1193	988	1158	1046	902	1034	39	40	40	40	40	41	42	44	44	44
1770	560	1046	881	1041	960	1039	914	1118	876	903	44	44	45	45	46	46	46	46	46	46
1780	1118	1064	1133	899	795	1037	1045	985	1074	1126	46	47	47	47	48	48	49	49	49	49
1790	955	907	1205	1049	785	820	922	1023	1175	900	49	49	50	50	50	50	50	50	50	50
1800	1170	798	1198	980	1155	1000	640	1033	1245	1057	51	51	51	51	51	51	51	51	51	51
1810	1183	1076	1306	994	931	949	904	1033	1236	776	52	51	51	51	51	51	51	51	51	51
1820	1037	787	1064	965	1015	960	618	1003	1044	925	51	51	51	51	51	51	51	51	51	51
1830	887	981	984	871	1105	1029	1322	1274	1113	995	51	51	51	51	51	51	52	52	52	52
1840	774	1101	1014	1184	966	1083	956	1009	992	954	52	49	49	49	49	49	49	49	49	49
1850	1250	1013	1157	949	937	910	1040	1297	936	807	49	48	48	48	48	48	48	48	48	48
1860	1018	1032	1208	1244	1001	936	1047	824	1015	834	48	47	47	47	47	47	47	47	47	47
1870	1042	927	783	794	959	960	887	1079	1085	1059	47	46	46	46	46	46	46	46	46	46
1880	932	1031	967	1083	1069	809	955	861	1224	1039	46	46	46	46	46	46	47	47	47	47
1890	958	978	1079	1056	864	1049	1052	918	977	1059	46	48	48	48	48	48	48	48	48	48
1900	1045	1140	1114	992	885	955	975	713	964	757	48	47	47	47	47	46	46	46	46	46
1910	957	1117	1024	1080	1004	1021	601	749	943	980	46	47	48	47	47	47	47	47	47	47
1920	961	936	1053	1276	1149	1003	1000	1108	710	991	47	48	48	48	48	48	48	48	48	48
1930	1014	980	1194	1131	1089	766	1204	1205	710	1035	48	45	45	45	45	45	45	45	45	45
1940	1073	1055	1222	913	1116	1134	1102	794	1045	1046	45	44	44	44	44	44	44	44	44	44
1950	885	911	1128	935	945	981	882	1173	1066	1238	44	43	43	43	43	43	43	43	42	42
1960	1053	1029	1002	1036	1011	980	979	937	933	1044	42	42	42	42	41	41	41	41	41	40
1970	991	852	1079	992	1038	974	1227	1145	925	986	40	40	40	40	39	38	38	7	7	7
1980	941	1104	1263	1357	437	1039	776	1036	836	1097	7	7	7	7	7	7	7	6	6	6
1990	987	1058	1036								6	6	5							

Site and collection information (ARM)

Site name: Armstrong Reserve **Site abbr.:** ARM
Country: New Zealand **State or Province:** South Island
Latitude: 43°50'S **Longitude:** 173°00'E **Altitude:** 731m
Species collected: *Libocedrus bidwillii*
Date of collection: 10 February 1978
Collectors: P. W. Dunwiddie, K. Platt, J. Leathwick
No. of trees/cores sampled (original): 18/70 **No. of discs:** 0

Site description:

The site was described as following (LaMarche *et al.*, 1979):

Armstrong Scenic Reserve is located above the town of Akaroa on Banks Penisula.The site is in a stand of *Podocarpus totara* and *Nothofaqus fusca* forest (elevation 730 m) on the east slopes of Flag Peak in the headwaters above Flea Bay. Stony Bay Road from Akaroa provides close access to the site.

All *Libocedrus bidwillii* in the stand, of varying sizes and ages, are dead. Rot had begun on the outsides of most individuals, but all appeared to have died within a few years of each other, between 1950 and 1960. The site was fenced in 1969, but disturbance by grazing probably was considerable in the past, and may have contributed to the death of the trees. Living *Libocedrus* are present up to 1 meter tall in the tussock grass above the stand, but were stunted by excessive browsing and not cored. Trees in the stand are up to 16 m tall, and some are emergent from the canopy.

The slope averages 20° toward the south and east, and is moderately well-drained. Bedrock is primarily andesite and basalts, with moderate soil development. Understory growth in the stand is slight.

Summary of chronology statistics:

Chronology 1446 to 1958 (513 years) 18 trees 46 radii

Chronology type	STNDRD	RESID (AR 2)	ARSTAN
Mean	1.0000	1.0025	1.0042
Median	1.0067	1.0106	1.0143
Mean sensitivity	.1602	.1864	.1547
Standard deviation	.2202	.1646	.2142
Skewness	.0475	-.5649	.0090
Kurtosis	.3899	1.6415	.0626
Autocorrelation order 1	.5643	.0052	.5723
Partial autocorr order 2	.1377	.0495	.1369
Partial autocorr order 3	.0143	.0147	-.0085
Variance due to autoregression	36.0%		37.3%
Error variance	.005114		.003145
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.6149

Common interval 1741 to 1894 (154 years) 12 trees 22 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.314	.350
Between trees (Y variance)	.300	.336
Within trees	.592	.621
Signal-to-noise ratio	5.135	6.074
Agreement with population chron	.837	.859
Variance in first eigenvector	38.78%	42.22%
Chron common interval mean	.989	1.000
Chron common interval std dev	.196	.151

Chronology listings

Residual Chronology of ARM:

	Tree-Ring Indices										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1449										1129										1
1450	843	1027	1070	722	1108	1754	653	1134	1107	1010	1	1	1	1	1	1	1	1	1	1
1460	464	844	875	1031	1228	960	1315	853	560	903	1	1	1	1	1	1	1	1	1	1
1470	848	1007	1092	804	794	953	1079	903	1001	1155	2	2	2	2	2	2	2	2	2	2
1480	821	1252	853	610	1232	870	998	709	1168	1243	3	3	3	3	3	3	3	3	3	3
1490	778	719	760	989	669	996	1042	1146	1042	842	3	3	3	3	3	3	3	3	3	3
1500	816	1174	1663	1043	1045	1158	689	936	1030	1031	3	3	3	3	3	3	3	3	3	3
1510	1092	1149	910	1159	1054	1197	1072	1057	960	1095	3	3	3	3	4	4	4	4	5	5
1520	1012	1216	1199	1227	1077	1210	897	1219	1132	921	5	6	6	6	7	7	7	7	7	7
1530	1146	935	1240	1075	929	1076	1161	1219	917	795	7	8	8	8	8	8	8	8	8	8
1540	1008	568	950	811	958	789	1003	955	977	1060	8	8	8	10	10	10	10	10	10	10
1550	674	1056	980	1029	1058	917	802	1072	905	957	10	10	10	10	10	10	10	10	10	10
1560	1255	1309	1030	916	1132	1121	771	926	938	943	10	10	10	11	11	11	11	11	11	11
1570	1108	1094	928	1269	1065	974	912	1008	1102	802	11	11	12	12	12	12	12	12	12	12
1580	1032	1020	653	1162	1007	925	1103	1222	1211	1062	12	12	12	12	12	12	12	12	12	12
1590	1045	1031	845	1030	900	1197	970	918	672	1263	12	13	13	14	14	14	14	14	14	14
1600	1189	1193	365	993	986	908	965	1281	921	964	14	14	14	14	14	14	14	14	14	14
1610	1115	1208	434	1030	931	1155	733	949	1189	1047	14	14	14	14	14	14	14	14	14	14
1620	1009	941	929	1088	1103	898	1015	1107	1090	1150	13	13	13	13	13	14	14	14	14	14
1630	885	846	700	969	1147	863	1110	786	1109	987	14	14	14	14	14	14	14	14	14	15
1640	1143	1280	1103	1245	956	1112	921	1109	1093	836	15	15	15	15	14	14	14	14	14	14
1650	1120	984	601	994	790	950	1125	896	1161	991	14	13	13	13	13	13	13	14	14	14
1660	955	1056	675	1045	1126	1036	1088	1188	1002	1017	14	15	15	16	16	16	16	16	17	17
1670	785	1185	1495	954	1056	753	992	1061	855	1114	17	17	17	17	17	17	17	17	17	18
1680	1139	1200	1005	1126	921	1000	965	851	1024	980	18	18	19	19	19	19	19	19	20	22
1690	1094	902	942	936	1011	1077	935	958	934	830	22	21	22	22	22	22	22	22	23	23
1700	1017	981	1033	1088	913	787	1445	1109	896	962	23	24	24	24	24	24	24	26	26	26
1710	1082	1116	1098	996	1196	901	1047	1043	888	907	26	26	26	25	25	25	26	26	27	27
1720	571	936	955	1100	796	1069	1102	965	1285	790	27	28	28	28	28	28	28	28	28	28
1730	966	1148	1028	1110	1007	1081	1193	958	1019	909	28	31	32	32	34	34	34	34	34	34
1740	1017	668	903	1087	1043	1201	782	1089	1062	1179	35	36	36	36	36	36	36	36	36	36
1750	1008	1020	1085	1129	1010	964	1039	974	904	1080	36	36	36	36	36	36	36	36	36	36
1760	1093	956	986	1057	1100	944	1265	1125	962	1085	36	36	36	36	36	36	36	36	37	37
1770	694	966	970	952	859	994	988	996	940	1188	36	38	38	38	38	38	38	38	38	38
1780	1010	1039	1024	1252	866	986	1102	797	1112	1062	38	38	38	38	38	38	38	38	38	38
1790	719	897	1033	1137	799	1008	839	1207	1109	1229	38	38	38	38	38	38	38	38	38	38
1800	1074	1211	960	970	926	1160	1101	1081	614	891	38	38	38	38	38	38	38	38	38	37
1810	1071	943	1019	868	868	1167	1020	825	1049	942	37	37	37	37	37	37	37	37	37	37
1820	950	1191	1019	1064	1090	1238	1038	1274	1221	1090	37	37	37	36	36	35	35	35	35	35
1830	528	1069	931	817	603	856	964	1054	912	1089	35	34	32	31	31	31	31	31	31	31
1840	993	1321	913	974	1127	1162	867	502	919	967	31	31	32	32	32	31	30	30	30	30
1850	987	967	1118	1218	643	1110	1082	983	851	922	30	29	29	27	27	27	27	27	27	27
1860	1119	894	846	764	973	890	1032	899	1185	1186	27	27	27	27	27	27	27	27	27	27
1870	737	946	732	1132	998	1193	1258	1063	1166	967	26	26	26	26	26	26	26	26	26	25
1880	1176	904	1023	863	1056	1024	842	705	1007	974	25	25	25	25	25	25	25	25	25	25
1890	1061	1115	1100	1156	1119	882	1124	1095	1307	1146	25	26	26	26	26	25	24	24	24	24
1900	1174	1308	740	1141	1049	1061	1120	333	1171	1201	24	23	23	22	22	22	22	21	21	21
1910	962	1139	895	808	1104	1189	698	1131	918	989	20	20	20	20	20	18	18	18	18	17
1920	911	1170	1290	1039	677	1040	1103	912	1063	961	16	16	15	15	15	15	14	14	14	13
1930	806	1090	1154	1037	1068	550	884	985	874	833	11	11	10	10	10	10	10	10	9	9
1940	1051	803	788	891	1266	1046	1273	1288	735	1623	9	9	7	6	5	5	5	5	4	4
1950	1010	1135	580	842	655	847	879	713	815		4	4	4	3	3	2	2	1	1	

Site and collection information (CLW)

Site name: Clear Water **Site abbr.:** CLW
Country: New Zealand **State or Province:** North Island
Latitude: 39°37.5'S **Longitude:** 176°06.3'E **Altitude:** 1220m
Species collected: *Libocedrus bidwillii*
Date of collection: 27 January 1993
Collectors: L. Xiong; J. G. Palmer; B. E. Smith; J. Rogers
No. of trees/cores sampled: 18/49 **No. of discs:** 0

Site description:

This site is located on the Ohutu Ridge, about 2 km from site OHT and 5 km from Ohutu Hut. Access was by helicopter to Ohutu Hut. The forest consisted of a mixture of *Phyllocladus alpinus*, *Libocedrus bidwillii* and had a dense undergrowth of *Rubus spp*. High deer number in the close area had removed most of the understory species except the *Rubus spp.*

Summary of chronology statistics:

Chronology 1450 to 1991 (542 years) 18 trees 45 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	1.0000	1.0004
Median	.9802	.9928	.9858
Mean sensitivity	.1268	.1641	.1267
Standard deviation	.2230	.1557	.2083
Skewness	.5693	.2216	.5085
Kurtosis	.5430	1.4623	.5262
Autocorrelation order 1	.7064	-.0459	.6656
Partial autocorr order 2	.0982	.0110	.0308
Partial autocorr order 3	-.0212	.0147	-.0196
Variance due to autoregression	51.0%		47.5%
Error variance	.017504		.011294
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.6452

Common interval 1803 to 1985 (183 years) 16 trees 33 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.288	.356
Between trees (Y variance)	.280	.349
Within trees	.439	.487
Signal-to-noise ratio	6.224	8.579
Agreement with population chron	.862	.896
Variance in first eigenvector	32.01%	38.00%
Chron common interval mean	1.012	1.002
Chron common interval std dev	.198	.146

Chronology listings

Residual Chronology of CLW:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1453				877	1145	1350	713	1087	1249	482
1460	1137	825	1023	946	1141	998	445	1332	763	738
1470	961	806	1142	957	1535	1032	1220	707	884	810
1480	1152	1350	1150	1385	953	835	654	1302	1023	735
1490	927	1084	950	1031	1069	729	1213	961	1213	1040
1500	1071	1337	956	810	1361	1388	1039	1018	769	1588
1510	981	758	945	844	912	784	1081	900	858	1095
1520	834	1024	1048	1008	896	926	1058	1094	910	885
1530	1312	821	856	912	723	1018	960	1064	1090	1073
1540	1116	1116	944	879	825	875	891	909	963	1096
1550	1266	1324	1346	689	881	936	1040	951	1054	1029
1560	1120	965	942	937	913	839	901	845	882	1104
1570	824	922	1268	1016	955	856	1095	1020	1002	1234
1580	954	922	865	894	916	1206	1041	1066	1114	1426
1590	955	995	1019	1004	1441	842	1475	991	880	619
1600	842	929	883	819	993	945	977	807	861	845
1610	1005	1019	896	960	855	1029	922	1036	1049	1053
1620	883	985	915	901	1145	929	1062	1133	962	1126
1630	1047	970	1148	690	851	1099	1161	806	862	881
1640	1057	1194	1029	1107	936	1198	977	1157	1052	978
1650	957	1062	592	1054	961	991	1127	957	1025	827
1660	885	1132	1104	1150	871	870	983	1013	1066	1003
1670	775	1254	1176	779	1084	928	1103	1243	755	991
1680	962	1034	1029	1021	926	1044	909	1139	1154	1069
1690	1095	1055	1146	1153	961	984	931	951	896	904
1700	945	963	1035	996	840	993	1313	994	756	967
1710	998	1133	1072	834	1095	975	915	909	1000	1137
1720	1201	1080	991	1062	1125	1229	1043	1046	1505	694
1730	1386	895	927	1175	1130	922	1240	814	900	1039
1740	1029	513	915	1060	821	904	933	1001	986	1050
1750	919	1002	761	953	998	1006	902	975	908	1031
1760	1166	1046	948	970	901	977	1127	841	893	1130
1770	858	883	1013	950	922	1018	1000	1215	1078	1051
1780	1044	998	777	1022	1019	1075	1022	939	971	1006
1790	986	882	872	1055	945	885	989	990	969	1291
1800	1224	1105	1021	898	1265	1151	907	1073	956	883
1810	872	1126	902	986	1244	1246	911	977	1111	1076
1820	845	1031	949	1035	1051	1409	707	1281	1131	1155
1830	677	1036	861	853	1138	1059	930	935	977	1043
1840	935	1203	917	916	947	933	823	761	918	864
1850	980	989	1061	955	1022	967	1086	1081	907	1058
1860	906	1267	974	1237	1104	680	1178	843	1060	1039
1870	984	1137	660	1233	1175	1055	1040	985	1182	1401
1880	1012	926	1040	557	797	1080	1019	857	913	1053
1890	980	1032	1031	971	939	987	1201	1019	1130	1069
1900	1099	1068	907	1008	1127	1000	890	637	1131	1197
1910	839	902	797	1100	1096	1138	684	1107	882	937
1920	918	1146	957	955	855	829	1068	872	927	940
1930	792	1118	1392	1256	1347	537	982	1117	837	697
1940	1113	943	1015	1124	1079	879	1012	1089	951	1060
1950	1152	1072	952	971	833	1002	1014	1106	1067	1145
1960	937	921	1018	953	959	1111	952	1233	881	1040
1970	1004	1082	944	1092	963	936	993	1038	827	1025
1980	1012	1056	991	1061	969	901	936	1148	1020	1182
1990	841	1023								

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1453				1	1	1	1	1	1	1
1460	1	1	1	1	1	1	2	2	2	2
1470	2	2	2	2	2	2	2	2	2	2
1480	2	2	2	2	2	2	2	2	2	2
1490	2	2	2	2	2	2	2	2	2	2
1500	2	2	2	2	2	2	2	2	2	2
1510	2	2	2	2	2	2	2	2	2	2
1520	2	2	2	2	2	2	2	2	2	2
1530	2	3	3	3	3	3	3	3	3	3
1540	3	3	3	3	3	3	3	3	3	3
1550	3	4	4	4	4	4	4	4	4	4
1560	4	4	4	4	4	4	5	5	5	5
1570	5	5	5	5	5	5	5	5	5	5
1580	5	5	5	5	5	5	5	5	5	5
1590	5	5	5	5	5	5	5	5	5	5
1600	5	5	6	6	6	6	6	6	6	6
1610	6	6	6	6	6	6	6	7	8	8
1620	8	8	8	8	8	8	10	10	10	10
1630	10	10	10	10	10	10	10	10	10	10
1640	11	12	12	12	12	12	12	12	12	12
1650	12	13	13	13	13	13	15	15	15	15
1660	15	15	15	15	15	15	15	15	16	16
1670	16	16	16	16	17	17	18	18	18	18
1680	18	18	19	19	19	19	19	19	19	19
1690	19	19	19	19	19	19	19	19	20	20
1700	20	21	21	22	22	22	22	22	22	22
1710	22	23	23	23	24	24	24	24	24	24
1720	24	24	24	24	24	24	24	24	24	24
1730	24	24	24	24	24	24	24	24	24	24
1740	25	25	25	25	25	25	25	25	25	25
1750	25	27	28	28	28	28	28	28	28	28
1760	28	29	29	29	29	29	30	30	30	30
1770	30	30	30	30	30	30	30	30	31	31
1780	31	31	31	31	32	32	32	32	32	33
1790	34	36	36	36	36	36	36	36	36	36
1800	36	37	38	38	39	39	39	39	39	39
1810	39	39	39	39	39	39	39	39	39	39
1820	39	39	39	39	39	39	39	39	39	39
1830	39	40	40	40	40	40	40	40	40	40
1840	40	41	41	41	41	41	41	41	41	41
1850	41	42	42	43	43	43	43	43	43	43
1860	43	43	43	43	43	43	43	43	43	43
1870	43	42	42	42	42	42	42	43	43	43
1880	43	43	43	43	43	43	43	43	43	43
1890	43	43	43	43	43	43	43	43	43	43
1900	43	42	42	42	42	42	42	42	42	42
1910	42	42	43	42	42	42	42	42	42	42
1920	42	42	42	42	42	42	42	42	42	42
1930	42	42	42	42	42	42	42	42	42	42
1940	41	41	41	41	41	41	41	41	41	41
1950	41	41	40	40	40	40	40	40	40	40
1960	40	40	40	40	40	40	40	40	40	40
1970	40	40	40	40	40	40	40	40	40	40
1980	40	40	40	40	40	40	39	39	39	39
1990	37	37								

Site and collection information (CRC)

Site name: Cream Creek **Site abbr.:** CRC
Country: New Zealand **State or Province:** South Island
Latitude: 43°05'S **Longitude:** 170°59'E **Altitude:** 800m
Species collected: *Libocedrus bidwillii*
Date of collection: January 1980
Collectors: D. A. Norton; A. E. Moore
No. of trees/cores sampled (original): 106/182 **No. of discs:** 3

Site description:

Refer to Norton (1983a) for details.

This site is located in the Cropp River catchment, a tributary of the Whitcombe and Hokitika Rivers. Access was by helicopter; foot access from the Hokitika River road end (35 km south of Hokitaki township) takes two days. The site is approaximately 1.5 km downstream from the NZ forest Service Cropp River hut and is located on the true right-hand side of the river. The stand is below Reckless Torrent and approximately opposite a prominent (ultramafic) rockbluff on the true left. Cream Creek (unofficial name) is an inconspicuous stream where it joins the Cropp River, but forms a long vegetated slip in its upper reaches and bounds the west (upstream) side of the stand.

The forest consists of *Archeria traversii*, *Dracophyllum traversii*, *Myrsine divaricata* and *Olearia ilicifolia* forming a low canopy at 3-4 m. *Griselinia littoralis* is abundant in the subcanopy. The cored *Libocedrus bidwillii* trees are scattered through the forest and grow as emergents above the main canopy. A dense ground cover of shrubs, tree seedlings, herbs, ferns and bryophytes is present.

Summary of chronology statistics

Chronology 1460 to 1978 (519 years)	15 trees	25 radii	
Chronology type	STNDRD	RESID (AR 2)	ARSTAN
Mean	1.0000	1.0000	1.0119
Median	.9937	.9989	1.0147
Mean sensitivity	.1659	.0000	.1595
Standard deviation	.2885	.1914	.2912
Skewness	1.7053	-.4447	1.4786
Kurtosis	9.9183	4.6979	8.4174
Autocorrelation order 1	.6608	-.0267	.6890
Partial autocorr order 2	-.0157	-.0151	-.1030
Partial autocorr order 3	-.1284	.0397	-.1163
Variance due to autoregression	44.3%		49.9%
Error variance	.028467		.025434
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.8935

Common interval 1760 to 1978 (219 years)	13 trees	20 radii
	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.297	.327
Between trees (Y variance)	.286	.318
Within trees	.595	.565
Signal-to-noise ratio	5.203	6.053
Agreement with population chron	.839	.858
Variance in first eigenvector	33.94%	36.40%
Chron common interval mean	.995	1.004
Chron common interval std dev	.223	.155

Chronology listings

Residual Chronology of CRC:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1462			1843	-285	832	634	821	1163	769	581
1470	1009	914	1055	1006	772	807	851	1247	1456	688
1480	1324	1054	1220	1371	668	505	882	995	1069	1312
1490	514	1148	1159	937	870	1233	748	1411	958	901
1500	1157	1170	1162	811	941	908	1224	718	1272	762
1510	872	719	819	1143	936	1174	1368	412	1201	491
1520	771	869	983	995	953	949	721	1032	817	942
1530	1047	862	1031	1317	985	945	1161	852	1007	838
1540	1086	1392	1144	1165	1071	1196	958	999	1044	1308
1550	946	928	1015	1561	1462	856	874	1405	708	857
1560	1143	734	1136	511	1154	887	427	965	1140	1001
1570	1110	1585	1367	1039	1266	1169	642	825	1156	974
1580	958	634	738	887	1018	1156	1169	1102	732	837
1590	1096	1104	1203	1115	846	1053	942	869	1108	1004
1600	977	897	1083	923	1116	1217	585	1090	1042	1051
1610	992	498	765	992	747	1188	802	973	1313	965
1620	1437	934	743	1092	1083	976	1152	1293	849	1148
1630	1365	878	1492	1025	688	840	1218	939	704	901
1640	1079	1167	879	783	1028	1011	961	1113	825	830
1650	969	832	720	988	1025	1133	1102	922	916	958
1660	925	1132	978	1045	876	947	1310	1096	1117	1048
1670	929	1345	1019	1005	1127	853	995	1055	1020	1068
1680	936	1165	888	1031	948	1096	813	688	1046	1076
1690	1291	969	897	1062	1074	1046	1007	1018	1041	989
1700	1019	1077	819	1255	995	945	1102	738	826	1101
1710	853	968	1023	858	1193	1004	904	914	663	849
1720	1099	1014	1145	1052	1057	1118	930	1102	1333	852
1730	1141	959	912	936	927	1269	1083	892	923	1278
1740	893	838	967	1001	1125	1207	1136	942	1171	894
1750	766	1237	1007	1006	937	987	1063	1080	1045	1049
1760	906	908	1027	957	1090	963	971	951	1046	965
1770	703	1011	852	949	943	984	867	1183	1064	1049
1780	1110	1048	873	998	1015	1014	1155	979	1000	1057
1790	859	914	1038	967	980	850	972	1185	860	873
1800	1312	1138	1111	904	1309	1348	588	570	945	1014
1810	1118	1072	1196	824	1157	1157	1059	803	801	996
1820	1040	1013	985	1061	1086	1222	759	1220	1024	1013
1830	799	973	800	814	1175	1217	1118	941	1077	941
1840	1233	1302	865	964	876	1227	948	1072	992	874
1850	731	929	990	1023	1032	1108	802	995	853	803
1860	830	1077	936	984	1147	1052	1119	911	1104	1057
1870	1107	969	1028	1218	1195	1119	857	1114	693	1283
1880	959	1050	997	1070	1046	1184	1029	955	957	1170
1890	981	1100	1319	1119	708	722	1515	929	772	1023
1900	1046	940	1044	900	914	857	947	921	1032	970
1910	967	1049	966	1157	937	1126	872	1261	968	978
1920	1011	1050	934	794	1031	879	978	1118	905	1060
1930	1033	1092	1146	1123	990	518	810	928	718	903
1940	1213	1116	949	987	1065	904	999	1056	1198	957
1950	1293	635	1135	1103	1061	950	992	946	742	853
1960	1260	908	858	917	884	1036	899	1051	732	753
1970	1156	1317	1451	1374	1148	1020	1113	1162	853	

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1462			1	1	2	2	2	2	2	2
1470	2	2	2	2	2	2	2	2	2	2
1480	2	2	2	2	2	2	2	2	2	2
1490	2	2	2	2	2	2	2	2	2	2
1500	2	2	2	2	2	2	2	2	2	2
1510	2	2	2	2	2	2	2	2	2	2
1520	2	2	2	2	2	2	2	2	2	2
1530	2	2	2	2	2	2	2	2	2	2
1540	2	2	2	2	2	2	2	2	2	2
1550	2	2	2	2	2	2	2	2	2	2
1560	2	2	2	2	2	2	2	2	2	2
1570	2	2	2	2	2	2	2	2	2	2
1580	3	3	3	3	3	3	3	3	3	3
1590	3	3	3	3	3	3	3	3	3	3
1600	3	3	3	3	3	3	4	4	4	4
1610	4	5	5	5	5	5	5	5	5	5
1620	5	5	5	5	5	5	5	6	6	6
1630	6	6	6	6	6	6	6	6	6	6
1640	6	6	6	6	7	7	7	7	7	7
1650	7	7	7	7	7	7	7	7	7	7
1660	7	7	7	7	7	7	7	7	8	8
1670	8	8	8	8	8	8	8	8	8	8
1680	8	8	8	8	8	8	8	8	9	9
1690	9	9	9	9	9	9	9	9	9	9
1700	9	9	10	11	11	11	11	11	11	11
1710	11	11	11	11	12	12	12	12	12	13
1720	13	13	13	13	13	13	14	14	14	14
1730	16	16	16	16	16	17	17	17	17	17
1740	17	17	17	17	17	17	18	18	18	18
1750	18	19	19	19	19	19	19	19	19	20
1760	20	20	20	20	20	20	20	20	20	20
1770	21	21	21	21	21	21	21	21	21	21
1780	21	21	21	21	21	21	21	21	21	21
1790	21	21	21	22	22	22	22	22	22	22
1800	22	22	22	22	22	23	23	23	23	23
1810	23	23	23	23	23	23	23	23	23	23
1820	23	23	23	23	23	23	23	23	23	23
1830	23	23	23	23	24	24	24	24	24	24
1840	24	24	24	24	24	24	24	24	24	24
1850	25	25	25	25	25	25	25	25	25	25
1860	25	25	25	25	25	25	25	25	25	25
1870	25	25	25	25	25	25	25	25	25	25
1880	25	25	25	25	25	25	25	25	25	25
1890	25	25	25	25	25	25	25	25	25	25
1900	25	25	25	25	25	25	25	25	25	25
1910	25	25	25	25	25	25	25	25	25	25
1920	25	25	25	25	25	25	25	25	25	25
1930	25	25	25	25	25	25	25	25	25	25
1940	25	25	25	25	25	25	25	25	25	25
1950	25	25	25	25	25	25	25	25	25	25
1960	25	25	25	25	25	25	25	25	25	25
1970	25	25	25	25	25	25	25	25	25	

Site and collection information (CRG)

Site name: MT. Cargill **Site abbr.:** CRG
Country: New Zealand **State or Province:** South Island
Latitude: 45°50'S **Longitude:** 170°32'E **Altitude:** 576m
Species collected: *Libocedrus bidwillii*
Date of collection: 9 May 1977
Collectors: P. W. Dunwiddie, D. A. Campbell
No. of trees/cores sampled (original): 16/61 **No. of discs:** 0

Site description:

Refer to LaMarche *et al.* (1979a) in detail. They described the site as:

The site is just north of the city of Dunedin, on the slopes of Mt. Cargill. Pinehill Road is followed to the television transmitting tower at the summit. Subsite I is about 100 m down the north side, below very dense shrubs regrowing after a burn. *Libocedrus bidwillii*, averaging 13 m tall, are emergent from 5 m tall shrubs, and appear to have been outside the burned area. Epiphytic mosses and ferns are abundant. The slope varies from 10° to 25°, with moderate soil development on an igneous substrate.

Subsite II is on a 20 east-southeast facing slope, south of the transmitting tower. Large (greater than one m dbh) *Nothofaqus menziesii* are found in a limited stand about 0.5 km below the road. The trees have been studied previously by Alan Mark (Univ. of Otago), and some have labels. This is the only stand of *N. menziesii* in the area.

Summary of chronology statistics:

Chronology 1492 to 1975 (4 years) 12 trees 43 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	1.0000	.9983
Median	.9892	1.0059	.9890
Mean sensitivity	.1618	.1924	.1544
Standard deviation	.2518	.1715	.2366
Skewness	.3619	-.6483	.2323
Kurtosis	1.2977	1.6568	1.3207
Autocorrelation order 1	.7039	.0208	.6882
Partial autocorr order 2	.1105	.0045	.0046
Partial autocorr order 3	.0590	.0403	.0153
Variance due to autoregression	43.7%		43.9%
Error variance	.007813		.006092
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.7798

Common interval 1877 to 1975 (99 years) 9 trees 29 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.404	.381
Between trees (Y variance)	.384	.363
Within trees	.612	.560
Signal-to-noise ratio	5.608	5.139
Agreement with population chron	.849	.837
Variance in first eigenvector	43.56%	40.81%
Chron common interval mean	1.006	1.001
Chron common interval std dev	.196	.138

Chronology listings

Residual Chronology CRG:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1496							980	779	1049	1014
1500	997	1177	667	1017	1323	1092	892	879	918	1160
1510	1245	837	915	997	893	1155	1176	924	837	1011
1520	910	931	949	1222	1141	966	916	1056	876	958
1530	1230	932	769	1340	1311	1248	1260	1174	1249	897
1540	1388	1095	984	934	1045	780	1136	987	929	860
1550	478	924	913	991	1170	973	887	1172	977	1189
1560	1006	961	994	763	1087	956	464	1037	1040	1232
1570	1391	1320	1173	1525	1181	1139	573	966	1332	747
1580	1284	964	460	1329	1101	976	920	1209	864	1159
1590	1032	907	580	1236	1087	1099	924	695	503	1116
1600	1155	993	527	971	915	984	883	1044	946	887
1610	1066	962	958	1123	956	1122	683	974	1149	830
1620	962	924	1032	1255	1239	984	1126	1105	1097	1012
1630	1070	836	869	1314	1389	589	1231	818	1229	910
1640	1304	1069	1069	1189	1017	1017	775	672	1017	810
1650	989	992	559	1096	900	1117	1095	733	1340	1186
1660	969	1037	520	962	880	897	487	978	1186	1067
1670	904	1083	993	931	994	617	943	935	839	1076
1680	1137	1297	895	1351	1164	1319	848	562	1293	1046
1690	1002	842	1066	1387	1338	1263	1037	1403	976	664
1700	1105	1053	1118	1075	855	396	1162	962	968	1067
1710	951	1080	871	939	1068	725	1052	1001	1049	891
1720	659	1168	1020	866	617	1175	1340	1023	1192	694
1730	1013	793	914	1016	545	1023	1077	977	1056	1122
1740	888	333	1067	789	1078	907	874	1118	1043	942
1750	1033	960	943	1185	930	869	883	1056	1202	1063
1760	1155	1098	989	1016	1112	922	1037	1184	1027	1134
1770	846	1051	1016	978	910	899	895	1163	803	1142
1780	860	979	1045	981	923	930	1084	866	1086	958
1790	874	1006	1079	1060	1008	1016	995	1199	992	1192
1800	1057	1087	1224	992	1073	1060	1086	1036	822	1044
1810	955	839	1031	978	1008	1175	987	881	949	974
1820	1042	748	1141	856	1078	959	944	1054	1029	1084
1830	806	1105	936	790	940	1023	1082	1115	991	1017
1840	982	1122	1084	925	1117	1137	799	790	1077	1066
1850	1003	1082	1140	1026	537	1109	1013	991	1047	1001
1860	1061	1078	889	929	993	876	1056	951	1043	1057
1870	868	949	663	1134	1077	1159	1088	1215	1095	1115
1880	1109	949	969	1025	983	863	971	815	1034	988
1890	1173	1059	1036	1095	902	971	1030	995	1075	1094
1900	966	947	996	853	956	992	821	459	1168	870
1910	1088	1087	847	793	1242	1086	879	1255	1090	1101
1920	928	1273	1016	968	554	1066	1006	991	1166	1072
1930	969	1064	1286	1089	980	829	1264	847	647	881
1940	1097	940	1039	983	1096	1113	970	1142	892	1117
1950	922	1087	1016	1047	927	870	750	949	987	995
1960	963	914	1130	1044	1107	1109	872	1170	1076	944
1970	882	930	930	1045	965	1102				

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1496							1	1	1	1
1500	1	1	1	1	1	1	1	1	1	1
1510	1	1	1	1	1	1	1	1	1	2
1520	2	2	2	2	2	2	2	2	2	2
1530	2	2	2	2	2	2	2	2	2	2
1540	2	2	2	2	2	2	2	2	2	2
1550	2	2	2	2	2	2	2	2	2	2
1560	2	2	2	2	2	2	2	2	2	2
1570	2	2	2	2	2	2	2	2	2	2
1580	2	2	2	2	3	4	4	4	4	4
1590	4	4	4	4	4	4	4	4	4	4
1600	4	4	4	4	4	4	4	4	5	5
1610	5	5	5	5	5	5	5	5	5	5
1620	5	5	5	5	5	5	5	5	5	5
1630	5	5	5	5	5	5	5	5	5	5
1640	5	5	5	5	5	5	5	5	5	5
1650	5	5	5	5	5	5	5	5	5	5
1660	5	5	5	5	5	5	5	5	5	5
1670	5	5	5	5	5	5	5	5	5	5
1680	5	5	5	5	5	5	5	5	5	5
1690	5	5	5	5	5	5	5	5	5	5
1700	5	5	5	5	5	5	5	5	5	5
1710	5	5	5	5	5	5	5	5	5	5
1720	3	3	3	3	3	4	4	4	4	4
1730	4	4	4	4	4	4	4	3	3	4
1740	4	4	4	4	4	4	4	4	4	4
1750	5	5	5	5	5	5	6	6	6	7
1760	7	7	7	8	8	8	9	9	10	10
1770	10	10	10	10	10	10	10	10	10	10
1780	10	9	9	9	9	9	9	9	9	9
1790	10	10	10	10	10	10	10	11	11	11
1800	11	12	12	12	13	13	13	14	14	15
1810	15	18	18	18	18	19	20	23	23	24
1820	24	25	25	26	26	27	27	27	27	27
1830	27	27	27	27	27	27	27	28	28	28
1840	28	28	28	28	28	28	27	29	30	30
1850	30	30	30	31	31	31	31	31	31	31
1860	31	31	31	31	31	31	31	31	32	32
1870	32	32	33	34	35	35	36	38	38	38
1880	38	38	38	38	38	38	38	38	38	38
1890	38	38	38	38	38	38	38	38	38	38
1900	38	38	38	38	38	37	36	34	34	34
1910	34	34	34	34	34	34	34	34	34	34
1920	34	34	34	34	34	34	34	33	33	33
1930	33	33	33	33	33	33	33	33	33	33
1940	33	33	33	33	33	33	33	33	33	33
1950	33	33	33	33	33	33	29	29	29	29
1960	29	29	29	29	29	29	29	29	29	29
1970	29	29	29	29	29	29				

Site and collection information (EMT)

Site name: Mt. Egmont **Site abbr.:** EMT
Country: New Zealand **State or Province:** North Island
Latitude: 39°15'S **Longitude:** 174°05'E **Altitude:** 1050m
Species collected: *Libocedrus bidwillii*
Date of original collection: 14-15 May 1977
Original collectors: P. W. Dunwiddie, D. A. Campbell
No. of trees/cores sampled (original): 12/46 **No. of discs:** 0
Date of new collection: 30 December 1991
New collectors: J. O. Murphy
No. of trees/cores sampled (new): 9/13 **No. of discs:** 0

Site description:

Refer to LaMarche *et al.* (1979a) about the original collection information:

The site is in the subalpine forest on the southeast slopes of Mt. Egmont, in the Mt. Egmont National Park. It is located along the hiking track from Dawson Falls to Fanthams Peak, about 1.6 km above the road end at Dawson Falls Lodge.

Collections were made from 8 *Podocarpus hallii* and 12 *Libocedrus bidwillii* in the forests adjacent to the track. The former ranged from 2 m tall at the higher elevations where the forest grades into small shrubs, to 7 m tall lower down. The *Libocedrus* were scattered in the taller forest, and reached heights of 15 m. They were infrequent, with no apparent regeneration, and almost all individuals were cored.

The substrate is volcanic ash and lapilli, some of which has apparently fallen since trees began growth. Other disturbance appeared to be minimal. Epiphytic ferns and mosses are common due to abundant moisture.

Dr J. O. Murphy recollected the sample of this site in 1991. He passed the cores to us so that we can process to update the chronology. He collected the samples exactly from the same site as Dunwiddie's site.

Summary of chronology statistics:

Chronology 1616 to 1990 (375 years)	21 trees	59 radii	
Chronology type	STNDRD	RESID (AR 6)	ARSTAN
Mean	1.0000	.9993	.9965
Median	1.0125	1.0098	1.0038
Mean sensitivity	.1493	.1705	.1511
Standard deviation	.1835	.1501	.1730
Skewness	-.2242	-.5437	-.1482
Kurtosis	.0553	1.1706	.2871
Autocorrelation order 1	.4795	.0041	.4099
Partial autocorr order 2	.1121	-.0305	.1078
Partial autocorr order 3	.0794	-.0013	.1469
Variance due to autoregression	25.1%		24.5%
Error variance	.004659		.003090
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.6632

Common interval 1796 to 1963 (168 years)	18 trees	45 radii
	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.338	.398
Between trees (Y variance)	.328	.388
Within trees	.549	.602
Signal-to-noise ratio	8.766	11.410
Agreement with population chron	.898	.919
Variance in first eigenvector	36.48%	41.94%
Chron common interval mean	1.009	1.004
Chron common interval std dev	.184	.160

Chronology listings

Residual Chronology of EMT:

Date	Tree-Ring Indices 0	1	2	3	4	5	6	7	8	9	Number of samples 0	1	2	3	4	5	6	7	8	9
1623				856	1132	846	791	997	1073	1260				3	3	3	3	3	3	3
1630	898	1054	1138	667	1091	847	1099	834	817	863	3	3	4	4	4	5	5	5	5	5
1640	771	823	1005	1133	826	903	911	1030	1079	939	5	5	5	5	5	6	6	6	6	6
1650	957	950	626	1018	1117	983	1237	1098	950	795	6	7	8	8	8	8	8	8	8	8
1660	992	1032	1015	1051	1009	1050	1054	1121	1094	1080	8	8	8	8	8	8	8	8	8	8
1670	910	1306	1326	951	1081	808	1104	1076	1161	1145	8	8	9	9	9	9	10	10	10	10
1680	1026	822	693	953	979	846	868	763	1057	932	10	10	10	10	10	10	10	10	10	11
1690	980	970	1130	989	1109	1020	1032	1105	1110	891	12	12	12	12	12	12	12	12	13	13
1700	1087	1014	1068	1169	1004	814	1259	921	994	890	13	13	13	13	13	13	14	15	15	15
1710	1016	1030	1197	923	1185	906	963	967	1039	1032	17	18	18	18	18	18	19	20	20	20
1720	870	945	981	1137	794	1014	1085	1052	1401	953	20	20	21	21	21	21	21	22	22	23
1730	1112	666	1160	964	1014	884	1126	883	1054	1061	23	24	24	24	24	24	24	27	27	27
1740	941	545	1093	891	830	898	966	1070	1025	1043	27	28	28	30	30	31	32	32	32	32
1750	977	979	768	1119	1187	943	989	988	1140	1130	32	32	32	32	32	33	33	33	34	35
1760	937	1027	983	1070	924	750	1042	981	1010	986	35	35	37	37	37	37	38	38	39	39
1770	878	1089	1129	1113	1146	1066	894	1156	997	1145	40	42	43	43	43	44	44	46	46	46
1780	930	791	992	1067	1116	994	1222	978	1076	1161	46	47	47	47	48	48	48	49	49	49
1790	779	946	1040	831	1042	1091	1025	1246	905	1109	49	51	51	51	51	51	51	51	51	51
1800	1148	1071	864	974	1208	1051	1090	1047	871	1174	51	51	52	52	53	53	53	53	54	54
1810	974	806	1163	987	974	1111	994	807	1213	800	54	54	54	54	54	54	54	54	54	54
1820	1078	1023	858	1007	1233	952	870	997	1071	956	54	55	55	55	55	55	55	55	55	55
1830	599	932	948	949	833	950	962	1136	1342	994	54	54	54	54	54	54	54	54	54	55
1840	711	1275	1027	988	650	990	939	792	1139	876	56	56	56	56	57	57	57	57	57	57
1850	1002	985	1076	1045	597	897	1180	1016	958	1092	57	56	56	56	56	56	56	56	56	56
1860	998	983	1278	1122	1123	937	1161	1082	1227	985	56	56	56	56	56	55	55	55	55	55
1870	712	1058	736	1047	1074	976	1158	1063	1080	773	55	54	54	54	54	54	54	54	54	54
1880	1029	1099	1164	774	971	1134	1133	848	949	732	54	54	54	54	54	54	54	54	54	54
1890	1129	1145	1074	1030	1124	1125	1031	1129	955	1164	55	55	55	55	55	55	55	55	55	55
1900	960	1066	908	1020	848	1077	1096	555	1031	939	55	55	55	55	55	55	55	55	55	55
1910	945	958	869	917	1191	1124	673	1048	950	1113	55	55	55	55	55	55	55	55	55	55
1920	1055	1077	1056	1017	487	881	1235	988	893	949	55	55	55	55	55	55	55	55	55	55
1930	949	1122	1118	1101	1201	393	998	982	700	845	55	55	55	55	55	55	55	55	55	55
1940	1138	993	1279	1059	1281	1200	714	1055	1008	1028	54	54	54	54	54	54	54	54	54	54
1950	1155	1072	1186	1240	736	1047	976	1012	1094	1023	54	54	54	54	54	54	54	54	54	54
1960	933	1111	795	1265	1077	1040	712	844	741	1046	54	54	54	54	53	53	51	50	49	49
1970	997	978	1090	962	1021	918	892	879	861	809	49	47	47	47	47	47	8	8	7	7
1980	1072	879	1361	1421	1073	884	1204	1148	842	957	7	6	6	6	6	6	6	6	5	5
1990	690										5									

Site and collection information (FLG)

Site name: Batten Range/Flanagans Hut **Site abbr.:** FLG
Country: New Zealand **State or Province:** South Island
Latitude: 41°16.3'S **Longitude:** 172°35.5'E **Altitude:** 950m
Species collected: *Libocedrus bidwillii*
Date of collection: 9 February 1993
Collectors: L. Xiong, B. E. Smith
No. of trees/cores sampled: 20/33 **No. of discs:** 0

Site description:

This site is located in the Naton Saddle. Access was by driving through Baton Valley Road and Ellis River Road. Car was parked in Ford. Foot access from Ford along Baton River takes six hours. The site is approaximately in the range of 500 m - 1000 m from Flanagans Hut. Nearly all adult *Libocedrus bidwillii* trees were sampled in this site. There were reasonable number *Libocedrus bidwillii* seedlings in this site.

Summary of chronology statistics:

Chronology 1683 to 1991 (309 years) 20 trees 33 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	.9966	1.0001
Median	.9826	.9969	.9791
Mean sensitivity	.1236	.1564	.1222
Standard deviation	.1848	.1418	.1854
Skewness	.6051	.1215	.6972
Kurtosis	.4657	1.6219	.6593
Autocorrelation order 1	.6067	.0040	.6221
Partial autocorr order 2	.0473	-.0240	.0017
Partial autocorr order 3	.0036	.0718	.0011
Variance due to autoregression	38.2%		39.3%
Error variance	.004978		.003710

Ratio of error variance of chronologies (ARSTAN/STNDRD) .7452

Common interval 1840 to 1991 (152 years) 20 trees 31 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.398	.418
Between trees (Y variance)	.393	.413
Within trees	.556	.579
Signal-to-noise ratio	12.937	14.080
Agreement with population chron	.928	.934
Variance in first eigenvector	42.37%	44.22%
Chron common interval mean	.996	.999
Chron common interval std dev	.208	.162

Chronology listings

Residual Chronology of FLG:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1685						1004	871	1198	1245	930
1690	1383	701	973	881	1095	1211	933	942	950	1008
1700	1092	1225	1112	1415	962	804	1103	772	929	1231
1710	1043	1032	1368	924	1234	1070	1166	907	921	1059
1720	846	936	872	1009	1036	970	832	1006	983	822
1730	1060	1029	884	1135	1045	1024	1070	1099	916	1079
1740	1014	802	1101	1028	860	1118	901	1006	1096	910
1750	876	1134	903	847	933	1045	977	1022	1061	1137
1760	1150	884	1005	949	1019	802	1042	845	967	1152
1770	720	965	984	961	1002	1107	912	1109	974	977
1780	1075	1073	1079	997	951	1022	1147	880	920	1054
1790	823	928	911	837	878	877	924	957	954	1031
1800	1189	1058	1222	892	1325	1031	960	926	1097	961
1810	1116	964	1004	863	890	1154	1039	764	1057	844
1820	972	1005	1031	942	1156	1146	909	1148	1206	1076
1830	760	923	976	818	989	933	1048	946	1026	887
1840	900	1191	1091	935	931	1214	1132	762	1203	831
1850	1171	1028	1136	899	752	888	1017	1043	933	798
1860	1077	1341	1064	1164	1187	731	1287	766	1143	1093
1870	899	948	853	953	1109	1071	1024	1078	962	948
1880	857	851	1087	695	989	1121	943	730	953	1000
1890	997	1050	1044	1039	919	1001	1527	914	1114	1040
1900	1284	1050	994	1240	678	872	1056	798	1001	1132
1910	848	842	1043	1089	1014	1126	550	942	881	994
1920	970	1113	1027	958	729	795	1059	988	873	911
1930	854	1120	1220	1468	1231	425	939	1141	704	795
1940	1150	1298	1397	1216	944	901	1024	1081	958	1235
1950	1219	820	1092	1085	958	936	958	1096	937	958
1960	1036	857	758	1016	997	1168	892	1046	773	953
1970	999	984	1025	982	973	859	1037	925	878	959
1980	940	885	1021	1127	884	1066	1040	1235	970	1082
1990	932	1059								

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1685						1	1	1	1	1
1690	1	1	1	1	1	1	2	2	3	3
1700	3	3	3	3	3	3	4	4	5	6
1710	6	6	6	6	6	6	6	6	7	7
1720	7	8	8	8	8	8	8	9	9	9
1730	10	11	11	11	11	11	11	11	11	11
1740	11	11	11	11	11	11	12	12	12	13
1750	13	15	15	15	15	15	15	15	15	15
1760	15	16	16	16	16	17	17	17	17	17
1770	17	17	17	17	17	17	17	18	19	19
1780	19	19	19	19	19	19	20	20	20	20
1790	20	22	22	22	22	22	22	22	22	23
1800	23	23	23	24	25	25	25	25	25	25
1810	25	25	25	25	25	25	25	25	26	26
1820	26	26	26	26	26	26	26	26	26	26
1830	27	28	28	28	28	28	29	29	30	30
1840	31	31	31	31	31	31	31	31	31	31
1850	31	31	31	31	31	31	31	31	31	32
1860	32	32	32	32	32	32	32	32	32	32
1870	32	32	32	32	32	32	32	33	33	33
1880	33	33	33	33	33	33	33	33	33	33
1890	33	33	33	33	33	33	33	33	33	33
1900	33	33	33	33	33	33	33	33	33	33
1910	33	33	33	33	33	33	33	33	33	33
1920	33	33	33	33	33	33	33	33	33	33
1930	33	33	33	33	33	33	33	33	33	33
1940	33	33	33	33	33	33	33	33	33	33
1950	33	33	33	33	33	33	33	33	33	33
1960	33	33	33	33	33	33	33	33	33	33
1970	33	33	33	33	33	33	33	33	33	33
1980	33	33	33	33	33	33	33	33	33	33
1990	33	33								

Site and collection information (HIT)

Site name: Hihitahi
Site abbr.: HIT
Country: New Zealand
State or Province: North Island
Latitude: 39°32'S
Longitude: 175°44'E
Altitude: 976m
Species collected: *Libocedrus bidwillii*
Date of collection:
Collector(s): Geoff Rogers
No. of trees/cores sampled: 37/38
No. of discs: 12

Site description:

Very large *Libocedrus bidwillii*, up to 160 cm in diameter, are found in gently rolling terrain near Hihitahi. The site is near a ridge top above the "Para Farms" on the road between Waioura and Taihape. The area has been selectively logged, and may have some grazing at present. *Podocarpus totara, P. ferrugineus, P. spicatus*, and various shrubs are present in the forest, which is bisected by numerous logging tracks. The *Libocedrus* are emergent from the very open canopy, and all individuals appear old; no small or middle size trees were found. Most have rotten centers. Moisture and soil development are moderate.

The site or nearby was originally sampled by Dunwiddie *et al.* (LaMarche *et al.* 1979a) in 1978, but no chronologies produced. The new samples were obtained by Dr Geoff Rogers initially for die-back research. The cores and discs include relative high ratio of dead trees. He passed all the cores and discs to us so that we can develop the chronology.

Summary of chronology statistics:

Chronology 1431 to 1991 (561 years) 49 trees 52 radii

Chronology type	STNDRD	RESID (AR 2)	ARSTAN
Mean	1.0000	1.0000	1.0032
Median	.9916	1.0116	1.0007
Mean sensitivity	.1399	.1759	.1379
Standard deviation	.1976	.1567	.1916
Skewness	.2508	-.5060	.1248
Kurtosis	.2152	.9408	.4872
Autocorrelation order 1	.5830	.0044	.5638
Partial autocorr order 2	.0875	-.0465	.0641
Partial autocorr order 3	.0033	.0024	-.0160
Variance due to autoregression	33.8%		31.6%
Error variance	.005212		.004316
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.8280

Common interval 1565 to 1840 (276 years) 19 trees 19 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.219	.303
Between trees (Y variance)	.219	.303
Within trees	.000	.000
Signal-to-noise ratio	5.322	8.263
Agreement with population chron	.842	.892
Variance in first eigenvector	27.20%	34.41%
Chron common interval mean	.998	1.002
Chron common interval std dev	.176	.148

Chronology listings

Residual Chronology of HIT:

Date	Tree-Ring Indices 0	1	2	3	4	5	6	7	8	9	Number of samples 0	1	2	3	4	5	6	7	8	9
1433				1239	703	987	1429	1451	654	1108				1	1	2	2	2	2	2
1440	1488	850	513	632	787	659	1169	947	1120	1209	2	3	3	3	3	3	4	4	4	4
1450	1077	1040	572	1210	1170	921	771	1108	1226	1262	4	4	5	5	5	5	5	5	6	7
1460	741	1269	1158	1184	1191	1022	1125	952	482	974	7	7	7	7	8	8	8	8	8	8
1470	931	887	913	864	733	984	923	970	809	924	8	8	8	9	9	9	9	10	10	10
1480	1181	1153	998	1082	942	979	1029	684	833	1289	10	10	10	10	10	10	10	10	10	10
1490	1179	1030	1082	869	669	1183	961	1105	1108	927	10	10	11	11	11	11	11	11	12	13
1500	1080	1224	1010	896	883	1181	992	945	1047	837	13	13	14	14	14	14	14	14	14	14
1510	911	921	682	1106	837	906	1145	1042	1005	897	14	14	14	15	15	15	16	16	16	16
1520	926	948	1063	1020	964	846	984	944	945	936	16	16	16	16	16	16	16	16	16	16
1530	970	969	1212	1118	1128	1031	1194	1132	808	771	16	16	16	16	16	16	16	17	17	17
1540	948	738	908	924	945	1057	1082	1317	1165	1227	17	17	19	19	19	19	19	19	20	20
1550	1079	1185	450	1056	1188	1011	879	1020	982	1357	20	20	20	20	20	20	20	20	20	21
1560	871	1134	949	1005	985	1171	635	952	1015	935	21	21	21	21	22	22	22	22	22	22
1570	1029	1211	971	1129	1033	957	787	1053	1026	748	22	22	22	22	22	22	22	22	22	22
1580	1001	905	884	1245	1007	969	1211	1238	1166	962	22	22	22	22	22	22	22	22	22	22
1590	1073	944	864	1139	810	1063	980	810	741	1094	22	22	22	22	22	22	22	22	22	22
1600	1011	1082	576	1012	1222	1238	1130	1046	1075	1025	22	22	22	22	22	22	23	24	24	24
1610	1049	663	1020	1017	832	1014	877	1152	958	1216	24	24	24	24	24	24	24	24	24	24
1620	1074	1055	635	1102	1116	749	1031	1321	996	1191	24	24	24	24	24	24	24	25	25	26
1630	1136	1159	1055	767	953	998	1171	742	968	936	26	26	26	26	27	27	27	27	27	27
1640	963	1162	1036	886	954	1038	1020	1151	1055	1030	27	27	27	27	27	27	27	27	27	27
1650	1055	944	485	950	920	1051	1114	737	988	971	27	27	28	28	28	28	28	29	29	29
1660	904	1064	924	1089	1014	959	911	1124	1216	1262	29	29	29	29	29	29	29	29	29	29
1670	829	1213	1139	675	999	1012	1046	995	725	1211	30	30	30	30	30	30	30	30	30	30
1680	1052	1107	786	1099	982	1108	825	871	1077	1215	30	30	30	30	30	30	31	31	31	31
1690	947	875	1080	1155	922	1023	882	1028	1013	984	31	31	31	31	31	31	31	30	30	30
1700	1093	1091	910	1250	850	773	1158	1146	847	995	30	30	30	30	30	30	30	30	29	29
1710	956	1153	1090	822	1033	1052	1101	878	966	878	29	29	29	29	29	30	30	30	30	30
1720	1005	1006	927	999	890	1117	1014	1160	1323	873	31	32	32	32	32	32	32	33	33	33
1730	1246	508	901	1040	945	968	1191	1007	1050	1070	33	33	33	33	33	33	33	33	33	34
1740	923	571	999	1029	923	1009	817	938	1114	1104	35	35	35	35	35	35	35	35	35	35
1750	993	1056	516	964	1160	1049	844	1028	980	1041	34	34	34	34	34	34	34	34	34	34
1760	1104	1156	889	1121	1007	891	1124	697	858	1175	34	34	34	34	34	34	34	34	34	34
1770	834	992	1194	1085	1070	1047	779	1313	1077	1219	34	34	34	34	34	34	34	34	34	34
1780	954	865	867	920	971	930	1041	935	938	1132	34	35	36	36	36	36	36	36	36	36
1790	1054	906	882	1092	1060	1023	1072	1215	858	1182	36	37	37	37	38	38	38	38	38	38
1800	1152	1327	978	887	966	1247	1035	965	790	932	38	38	39	39	39	39	39	40	40	40
1810	962	974	974	937	1104	1116	954	978	1204	978	40	40	40	41	41	42	42	42	42	42
1820	1048	1145	950	1037	1078	1297	819	1203	1052	1058	43	44	44	44	44	45	45	46	46	46
1830	707	1078	974	743	899	1163	1057	1065	1078	1043	46	47	47	47	47	47	47	47	47	47
1840	791	1285	995	943	885	1096	746	745	1057	923	47	46	46	46	46	46	46	46	46	46
1850	978	1004	1068	945	828	1014	1049	1062	930	999	46	44	44	44	44	43	43	43	43	42
1860	902	1262	1046	1185	1093	643	1125	959	1109	1043	41	40	40	40	40	40	40	40	40	40
1870	977	1024	613	995	1022	1032	1090	964	908	1099	40	40	42	42	42	41	41	41	41	41
1880	996	1118	912	848	940	1081	805	1016	917	1063	41	41	41	41	40	40	40	40	40	40
1890	1168	1127	1029	1027	1026	1015	1241	984	1247	1173	40	40	40	40	39	39	39	39	39	39
1900	1200	1157	840	1001	778	1033	1010	550	1092	1158	39	39	39	39	39	38	38	38	38	38
1910	786	992	840	1064	953	1063	710	1167	861	1048	38	38	38	38	38	38	37	37	37	37
1920	987	1200	1032	1026	709	931	1157	1031	1138	1057	37	35	35	35	35	35	34	34	34	34
1930	929	1126	1197	1025	897	589	1019	1022	739	758	34	33	33	33	33	33	33	33	32	32
1940	979	1082	1091	1052	1075	961	1012	964	973	959	32	32	32	32	32	32	32	32	32	32
1950	998	1015	962	934	906	1023	987	1072	1096	1037	32	32	32	31	31	31	30	30	29	29
1960	1159	885	1109	1250	1260	1181	869	1002	772	1024	29	27	26	26	26	26	26	26	26	25
1970	942	1032	892	976	1084	1140	1181	790	764	914	25	20	19	19	19	18	18	18	18	16
1980	967	800	1014	1166	996	1180	901	1210	864	1302	15	14	14	13	13	13	13	13	13	12
1990	763	1053									12	12								

Site and collection information (MOA)

Site name: Moa Park
Site abbr.: MOA
Country: New Zealand
State or Province: South Island
Latitude: 40°56'S
Longitude: 172°56'E
Altitude: 1036m
Species collected: *Libocedrus bidwillii*
Date of collection: 9 December 1992
Collector(s): L. Xiong, J. G. Palmer, B. E. Smith; J. Murphy
No. of trees/cores sampled: 20/51
No. of discs: 0

Site description:

Refer to LaMarche (1979a) about the original collection information but no chronology was developed by them.

The forests around Moa Park in Abel Tasman National Park have abundant *Libocedrus bidwillii* in various size classes. The site is reached by hiking the trail from Canaan Downs, and trees were cored on the slopes just west of Moa Park Hut. These *Libocedrus*, some estimated to exceed 35 m in height, are emergent from a moderately dense, multi-layered forest of *Nothofagus menziesii* (15-20 m), *Dracophyllum traversii* (10 m), and *Griselinia litttoralis* (10 m). Understory shrubs of *Coprosma, Phyllocladus, Pseudowintera*, and *Myrsine* are common in the slightly north-sloping area. Soils appear well-developed and poorly drained. Disturbance appears slight, although grazing may occur in nearby areas, where dead and dying *Libocedrus* are abundant.

The site was resampled on the slopes just near Moa Park Hut. A chronology was produced.

Summary of chronology statistics:

Chronology 1490 to 1991 (502 years) 20 trees 49 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	1.0000	.9999
Median	.9896	1.0030	1.0051
Mean sensitivity	.1269	.1597	.1232
Standard deviation	.2112	.1388	.1798
Skewness	.3560	-.2747	.1017
Kurtosis	.7158	.3824	.1845
Autocorrelation order 1	.7139	-.0187	.6364
Partial autocorr order 2	.1026	-.0538	.0059
Partial autocorr order 3	.1064	.0391	.0700
Variance due to autoregression	51.9%		40.3%
Error variance	.005633		.003869
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.6867

Common interval 1656 to 1975 (320 years) 15 trees 29 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.216	.303
Between trees (Y variance)	.202	.294
Within trees	.533	.504
Signal-to-noise ratio	3.790	6.247
Agreement with population chron	.791	.862
Variance in first eigenvector	25.83%	33.25%
Chron common interval mean	1.009	1.003
Chron common interval std dev	.183	.137

Site and collection information (MWO)

Site name: Mangawhero River Bridge **Site abbr.:** MWO
Country: New Zealand **State or Province:** North Island
Latitude: 39°21'S **Longitude:** 175°29'E **Altitude:** 1000m
Species collected: *Libocedrus bidwillii*
Date of collection: 15 January 1978
Collectors: P. W. Dunwiddie, M. R. Boase
No. of trees/cores sampled (original): 21/69 **No. of discs:** 0

Site description:

Refer to LaMarche *et al.* (1979a) about the site description:

On the southwest slopes of Mt. Ruapehu in Tongariro National Park approximately 9 km north of Ohakune, the Ohakune Mountain Road crosses to the west side of the Mangawhero River. Subsite I is Located just west of the road above the bridge on a 15° southeast facing slope. Nature *Libocedrus bidwillii* up to 13 m tall are emergent from an 8 m tall forest of *Nothofagus solandri var cliffortioides*. Drainage is poor in the site, which is boggy in places. *Coprosma*, *Myrsine*, *Griselinia*, small *Phyllocladus alpinus*, and some young *L. bidwillii* are also present.

Subsite II is 0.7 km farther up the road, in a nearly level area immediately west of the road. The forest has an open canopy of 11 m tall *Lagarostrobos colensoi* with *L. bidwillii*, *N. solandri var. cliffortioides*, and *P. alpinus* with a moderate understory of shrubs and ferns. Drainage is poor, with *Sphagnum* found in the boggy places. The subalpine forest at both subsides is well-developed, with little of the stunting or deformation characteristic of the trees at timberline several km higher. Substrate is predominantly volcanic ash. Recent disturbance appeared to be negligible.

Summary of chronology statistics:

Chronology 1464 to 1976 (513 years) 21 trees 69 radii

Chronology type	STNDRD	RESID (AR 3)	ARSTAN
Mean	1.0000	1.0035	1.0023
Median	.9816	1.0073	.9879
Mean sensitivity	.1158	.1348	.1095
Standard deviation	.1549	.1195	.1660
Skewness	.5486	-.0664	.3324
Kurtosis	.5123	.1778	.3958
Autocorrelation order 1	.5616	-.0048	.6508
Partial autocorr order 2	.2026	-.0017	.2302
Partial autocorr order 3	.0931	-.0002	.1259
Variance due to autoregression	35.7%		45.3%
Error variance	.003431		.002208

Ratio of error variance of chronologies (ARSTAN/STNDRD) .6436

Common interval 1751 to 1965 (215 years) 19 trees 43 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.190	.276
Between trees (Y variance)	.177	.263
Within trees	.500	.573
Signal-to-noise ratio	4.087	6.794
Agreement with population chron	.803	.872
Variance in first eigenvector	23.09%	30.93%
Chron common interval mean	1.000	1.004
Chron common interval std dev	.159	.116

Chronology listings

Residual Chronology of MWO:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1470	665	1028	930	954	962	890	860	983	978	1025
1480	666	906	784	961	952	900	911	1026	854	888
1490	1000	1138	854	960	940	1098	919	969	1048	958
1500	1011	890	959	1063	1023	1171	959	832	1145	1086
1510	1026	1159	1078	1113	773	913	836	847	916	1117
1520	1056	974	1001	1105	865	847	1065	995	1033	1029
1530	1117	1163	1128	902	902	830	1099	1040	975	843
1540	1010	907	1037	921	920	1138	1044	1126	1054	1060
1550	995	1132	862	910	935	1074	1094	886	922	1014
1560	1045	855	1072	796	934	1118	1023	850	1032	1052
1570	1114	1211	918	1001	1007	1238	1067	759	1269	1194
1580	1119	1083	1011	1076	1337	1076	1103	1133	1218	852
1590	943	777	1183	1154	977	1111	926	794	1031	1230
1600	1133	1259	940	1157	914	1024	887	1028	1116	911
1610	1291	1104	890	997	963	1127	950	1182	906	897
1620	1015	1157	863	845	964	953	954	1127	933	924
1630	1149	1021	1281	643	757	955	1183	1008	979	844
1640	983	1098	962	1123	744	1036	801	951	995	842
1650	976	975	748	984	961	1030	1150	1016	1202	867
1660	743	960	1032	951	964	883	954	768	988	993
1670	893	1128	1152	1166	1074	993	909	1156	765	924
1680	842	1086	928	1139	1049	1034	838	1158	1101	1156
1690	1051	956	895	1088	1029	1195	892	1000	1053	863
1700	915	987	1098	1226	1111	918	1151	959	878	1037
1710	797	982	1301	1088	887	937	1008	875	737	1135
1720	1010	1055	844	1072	1203	864	1003	1030	1124	842
1730	1183	822	918	1055	946	1076	908	943	1022	1102
1740	1102	978	1108	1032	859	1168	905	1040	1160	1171
1750	890	1116	906	975	1010	1044	1120	1125	843	937
1760	1035	1149	1003	1035	1081	829	1243	818	954	1175
1770	888	1180	1165	1049	947	999	890	1129	1117	1021
1780	1170	894	872	1002	881	1047	1113	1045	880	968
1790	926	902	827	1074	1051	1041	1069	1265	892	1205
1800	1190	1104	1012	835	1021	1140	901	955	1046	888
1810	917	886	977	970	1021	1035	871	1016	1128	1085
1820	996	1023	1007	1011	1071	1179	793	1129	936	977
1830	1069	1001	763	823	1214	922	1069	987	991	1010
1840	855	1127	972	1021	924	1036	932	895	1130	899
1850	1047	1068	983	1086	951	910	951	981	937	1048
1860	933	1023	1000	1023	1026	908	1115	795	1005	1031
1870	961	1032	630	1086	1015	978	1012	983	1034	1174
1880	784	1077	943	815	962	998	1049	859	1015	1179
1890	1111	1211	1314	1288	1167	991	1096	882	1074	1039
1900	1073	1122	853	1015	973	974	1043	838	1006	1145
1910	930	943	894	1015	1005	970	887	1088	769	962
1920	936	1094	925	944	939	934	1060	1109	1136	972
1930	743	1123	1359	1126	1193	588	1033	1163	700	880
1940	959	864	1042	1044	1014	945	892	1057	879	955
1950	1025	912	973	1092	1026	995	1006	1108	1136	1131
1960	1079	901	911	1064	1018	1013	1035	1186	845	1042
1970	906	1090	1023	1005	944	932	1086			

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1470	1	2	2	2	2	2	2	2	3	3
1480	3	5	5	6	6	6	6	6	6	6
1490	6	6	6	6	6	6	8	8	8	8
1500	8	8	9	9	9	9	9	9	9	9
1510	9	9	10	10	10	10	10	10	10	10
1520	11	11	11	11	11	12	12	12	12	12
1530	12	12	12	12	12	12	12	12	12	12
1540	13	13	13	13	13	13	13	13	13	13
1550	14	14	14	14	14	16	16	16	16	16
1560	16	16	16	17	17	17	18	18	18	18
1570	18	18	18	18	18	19	19	19	19	19
1580	19	19	19	19	19	19	19	19	19	19
1590	19	19	19	19	19	19	19	19	20	20
1600	20	20	20	20	20	20	20	20	20	20
1610	21	21	21	21	21	21	21	21	22	22
1620	22	22	22	22	22	22	22	22	22	22
1630	22	23	23	23	23	23	23	23	24	24
1640	24	24	24	24	24	24	25	25	25	26
1650	27	27	27	29	29	29	30	30	30	30
1660	30	30	30	31	31	32	32	32	32	32
1670	32	32	32	32	32	32	32	32	32	32
1680	33	33	33	33	33	33	33	33	33	33
1690	34	34	34	34	34	34	34	34	34	34
1700	34	34	34	34	34	35	35	35	36	37
1710	37	37	37	36	36	37	39	39	39	39
1720	39	39	39	43	43	43	43	43	44	45
1730	45	45	45	46	47	47	47	47	47	48
1740	48	48	48	48	48	49	49	49	49	50
1750	51	52	52	52	52	52	52	52	52	52
1760	52	52	52	53	53	53	53	53	53	53
1770	53	53	53	53	53	53	53	53	53	53
1780	53	53	53	53	53	53	53	53	54	54
1790	55	55	55	55	55	55	55	55	55	55
1800	55	55	55	55	55	55	55	55	55	56
1810	56	56	56	57	58	58	58	58	59	59
1820	59	59	59	60	61	61	61	61	61	61
1830	61	61	61	61	61	61	61	61	61	63
1840	63	65	65	65	65	65	65	65	65	65
1850	65	65	65	65	65	65	65	65	65	65
1860	65	65	65	65	65	65	65	65	65	65
1870	64	64	64	64	64	64	63	63	64	64
1880	64	64	64	65	65	65	65	65	65	65
1890	65	65	65	65	65	65	65	65	65	65
1900	65	64	64	64	63	63	63	63	63	63
1910	63	63	63	63	63	63	63	62	62	62
1920	62	62	62	62	62	62	62	62	62	62
1930	62	62	62	62	62	62	62	62	62	62
1940	62	62	62	62	62	62	62	61	61	61
1950	61	61	61	60	60	60	60	59	59	59
1960	59	59	59	59	59	59	58	58	58	58
1970	58	57	57	57	57	57	56			

Site and collection information (NET)

Site name: North Egmont **Site abbr.:** NET
Country: New Zealand **State or Province:** North Island
Latitude: 39°17'S **Longitude:** 174°06'E **Altitude:** 991m
Species collected: *Libocedrus bidwillii*
Date of original collection: 30 January 1978
Original collectors: P. W. Dunwiddie, K. Buchan, M. R. Boase
No. of trees/cores sampled (original): 16/60 **No. of discs:** 1
Date of new collection: 1 January 1992
New collectors: J. O. Murphy
No. of trees/cores sampled (new): 11/18 **No. of discs:** 0

Site description:

Refer to LaMarche *et al.* (1979a) about the original collection information.

The North Egmont Chalet is on the northern slopes of the volcano in Egmont National Park. A 29 km road from New Plymouth provides access to the area. A restricted access road, known as the Translator Road, ascends the mountain above the Chalet.

Mature *Libocedrus* up to 13 m tall are common along the road in the rocky valley bottom with *Podocarpus hallii*. Those selected for coring are located between the ford where the road crosses the Ngatoro stream and the sharp turn farther up the valley. Drainage is good in the rocky soil, and disturbance appears slight.

Dr J. O. Murphy recollected sample from this site. He passed the cores to us so that we can process and update the chronology. He collected the samples exactly from the same site as Dunwiddie's.

Summary of chronology statistics:

Chronology 1625 to 1990 (366 years) 28 trees 69 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	1.0014	1.0004
Median	.9994	1.0011	1.0018
Mean sensitivity	.1440	.1689	.1394
Standard deviation	.1858	.1491	.1781
Skewness	-.0135	-.2793	-.1230
Kurtosis	.4234	.7383	.3747
Autocorrelation order 1	.5106	-.0130	.5257
Partial autocorr order 2	.0179	-.0951	-.0539
Partial autocorr order 3	.1522	.0781	.1151
Variance due to autoregression	30.8%		27.7%
Error variance	.004842		.003932
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.8121

Common interval 1758 to 1972 (215 years) 25 trees 49 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.323	.391
Between trees (Y variance)	.315	.384
Within trees	.593	.628
Signal-to-noise ratio	11.514	15.601
Agreement with population chron	.920	.940
Variance in first eigenvector	34.86%	40.90%
Chron common interval mean	1.000	1.001
Chron common interval std dev	.195	.159

Chronology listings

Residual Chronology NET:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1629										656
1630	654	1183	1237	949	959	903	1188	1176	863	744
1640	1167	890	844	1062	1095	941	783	835	888	867
1650	897	876	981	1160	1074	855	1077	998	936	980
1660	919	1070	970	950	1027	873	946	949	1081	1075
1670	1040	1235	1051	764	1180	918	1022	1033	963	1047
1680	860	909	835	1121	918	851	844	1107	966	809
1690	1017	1027	1026	967	1283	972	969	1130	1019	900
1700	1158	948	1027	1193	1080	931	1230	818	955	949
1710	1009	1022	1040	952	1174	946	1164	1029	1087	1045
1720	930	997	1025	964	728	1052	1045	1020	1216	1058
1730	1056	810	1155	948	1013	1044	1094	832	1107	1160
1740	917	602	1216	1022	1073	909	926	972	1038	1138
1750	1009	1019	818	1280	1262	846	1221	1131	923	954
1760	875	1064	951	972	885	827	978	1002	968	995
1770	799	1111	1118	971	1160	1051	967	1164	1029	1171
1780	881	799	1108	885	944	916	1150	924	995	1107
1790	962	909	946	902	1023	1056	884	1212	1062	1354
1800	1285	1087	1004	1022	1218	1087	976	1000	967	974
1810	814	842	1228	820	910	1094	936	768	1039	1005
1820	969	1052	928	1086	1188	996	811	1185	1134	823
1830	605	987	934	763	765	849	1010	1044	1156	924
1840	982	1321	1074	911	733	1276	1012	808	1237	859
1850	1139	1232	1193	950	626	1089	1104	1073	850	964
1860	832	988	1206	1229	1100	1087	1180	958	1244	980
1870	914	998	668	946	1068	1074	1199	1297	937	831
1880	1023	1108	1076	716	1024	1137	962	834	1007	990
1890	842	1173	1099	1074	934	953	1180	1340	1092	1135
1900	893	1117	932	790	841	1206	993	774	1172	951
1910	751	1205	892	1000	1215	1030	627	1394	868	1067
1920	909	1300	1032	955	464	829	1052	948	937	926
1930	864	1110	879	1061	972	466	1015	999	801	892
1940	1222	1106	1144	1054	1205	1058	752	881	952	1046
1950	1062	1240	1144	1139	678	920	985	1041	1022	1225
1960	1157	981	619	1330	1080	943	803	1101	837	1092
1970	1003	1133	987	1078	967	1107	1195	1102	1027	1072
1980	1408	652	995	1132	704	912	1008	1163	775	977
1990	927									

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1629										1
1630	1	1	2	2	2	2	2	2	3	3
1640	3	5	5	5	5	5	5	7	7	7
1650	7	7	7	8	8	8	8	8	8	8
1660	8	8	8	8	8	8	8	8	9	11
1670	11	12	13	13	13	15	15	16	17	18
1680	19	19	20	22	23	23	23	23	23	23
1690	23	24	24	24	24	25	25	26	26	27
1700	27	27	28	29	31	31	31	33	36	36
1710	37	38	41	41	41	41	42	42	42	42
1720	44	44	45	46	47	47	47	47	48	50
1730	50	50	50	50	50	51	53	54	55	56
1740	56	57	57	57	58	58	58	58	60	60
1750	62	62	64	64	64	65	66	66	67	67
1760	68	68	68	68	68	68	68	68	68	68
1770	68	69	69	69	69	69	69	69	69	69
1780	69	69	69	69	69	69	69	69	69	69
1790	69	69	69	69	69	69	69	69	69	69
1800	69	69	69	69	69	69	69	69	69	69
1810	69	68	68	68	68	68	68	68	68	68
1820	68	68	68	68	68	68	68	68	68	68
1830	67	67	67	67	67	67	67	67	66	66
1840	66	66	66	66	66	66	66	66	66	66
1850	65	64	64	64	64	64	64	64	64	64
1860	64	63	63	63	63	63	63	63	63	63
1870	63	63	63	63	63	63	63	63	63	62
1880	62	62	62	61	61	61	60	60	60	60
1890	60	59	59	59	59	59	59	59	59	59
1900	59	58	58	58	58	58	58	58	58	58
1910	58	58	58	58	58	58	58	58	58	58
1920	58	57	57	56	55	54	54	54	54	54
1930	54	53	53	53	53	52	52	52	52	52
1940	52	52	52	52	52	52	52	52	52	52
1950	52	52	52	52	52	52	52	52	52	52
1960	52	52	52	52	51	51	51	51	51	51
1970	51	51	51	50	50	50	50	10	10	10
1980	10	10	10	10	10	10	10	10	10	10
1990	10									

Site and collection information (OHT)

Site name: Ohutu Ridge
Site abbr.: OHT
Country: New Zealand
State or Province: North Island
Latitude: 39°37.3'S
Longitude: 176°07.7'E
Altitude: 1140m
Species collected: *Libocedrus bidwillii*
Date of collection: 26 January 1993
Collector(s): L. Xiong, J. G. Palmer, B. E. Smith; G. Rogers
No. of trees/cores sampled: 18/44
No. of discs: 0

Site description:

This site is located in the Ohutu Ridge. It is about 2 km from site CLW and 6 km from Ohutu Hut. Access was by helicopter. This was an extensive patch of *Libocedrus bidwillii* dominated forest with a dense understory of *Rubus spp.*

Summary of chronology statistics:

Chronology 1585 to 1991 (407 years) 17 trees 40 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	1.0000	1.0031
Median	.9865	.9914	.9946
Mean sensitivity	.1481	.1867	.1518
Standard deviation	.2297	.1837	.2170
Skewness	.6234	.5933	.5386
Kurtosis	2.4673	3.5507	3.2426
Autocorrelation order 1	.5839	-.0844	.5185
Partial autocorr order 2	.1125	.0249	.0222
Partial autocorr order 3	-.0106	-.0336	-.1002
Variance due to autoregression	45.2%		33.0%
Error variance	.009879		.008610
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.8716

Common interval 1812 to 1990 (179 years) 14 trees 25 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.321	.386
Between trees (Y variance)	.310	.378
Within trees	.565	.571
Signal-to-noise ratio	6.277	8.505
Agreement with population chron	.863	.895
Variance in first eigenvector	35.48%	41.38%
Chron common interval mean	1.005	1.002
Chron common interval std dev	.168	.139

Chronology listings

Residual Chronology of OHT:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1588									1250	1276
1590	615	1585	704	1180	1103	852	1332	991	956	426
1600	1401	616	1549	639	1346	2002	623	418	473	729
1610	831	1159	1267	1032	1228	863	1790	789	1093	761
1620	631	1027	1280	1158	1141	1208	1646	1033	1093	1162
1630	560	734	1492	689	981	1041	635	1055	725	1036
1640	1120	977	1277	1138	569	956	1157	1285	581	1353
1650	630	574	768	1113	1087	1057	952	1126	970	1354
1660	1030	771	1217	940	954	947	851	862	1171	707
1670	927	1025	1092	983	862	830	857	732	1494	1037
1680	952	1074	868	1232	1044	977	861	975	1127	900
1690	870	928	879	842	964	899	834	863	931	783
1700	992	1024	1023	908	903	877	1158	919	733	891
1710	914	999	1048	890	1055	968	997	861	807	1175
1720	1180	935	952	966	1342	1142	1043	1198	1368	1003
1730	1264	855	931	1160	1118	834	1020	860	900	1029
1740	1032	983	1110	1201	794	1115	850	940	970	987
1750	890	1048	961	1043	940	993	1035	1048	867	1056
1760	1117	1076	958	905	968	963	1084	983	939	1225
1770	821	982	1053	1002	932	961	1055	1227	1149	1006
1780	924	991	865	1034	1088	961	998	876	1004	988
1790	971	869	791	1025	915	940	1043	1099	915	1115
1800	1205	1052	1049	918	1172	1107	1002	1044	964	862
1810	869	1060	941	906	1275	1187	907	937	1129	1051
1820	914	973	983	968	1060	1265	838	1133	1048	1066
1830	859	1012	884	818	1065	1105	964	1013	1055	971
1840	1014	1282	923	983	913	982	869	791	990	959
1850	1097	1036	1114	936	1027	964	972	1037	917	1104
1860	892	1358	1077	1184	1093	751	1293	824	1103	975
1870	959	1006	600	1101	1055	953	940	974	986	1262
1880	997	1051	1015	619	890	1088	977	923	950	1179
1890	1045	1037	1070	1141	1035	945	1179	988	1087	938
1900	1015	1058	831	924	991	1082	885	724	1150	1277
1910	923	890	757	1155	1106	1251	739	1261	890	1084
1920	907	1202	908	902	761	846	1129	851	862	821
1930	713	960	1308	1284	1283	715	1047	1074	735	770
1940	1034	1003	1056	1213	1109	812	1008	1075	844	1031
1950	1066	1087	998	869	858	890	934	1087	1110	1167
1960	996	767	959	1064	987	1105	997	1196	884	1035
1970	980	1021	919	1035	1015	928	958	1040	787	1040
1980	1090	974	1193	1205	921	960	882	1168	1030	1166
1990	906	1129								

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1588									1	1
1590	1	1	1	1	1	1	1	1	1	1
1600	1	1	1	1	1	1	1	1	1	1
1610	1	1	1	1	1	1	1	1	1	1
1620	1	1	1	1	1	1	1	1	1	1
1630	1	1	1	1	1	1	1	1	2	2
1640	2	2	2	2	2	2	2	2	2	2
1650	2	2	2	2	2	2	2	2	2	2
1660	2	2	2	2	2	2	2	2	2	2
1670	2	2	2	2	2	2	3	3	3	3
1680	3	3	3	3	3	3	3	3	3	3
1690	3	3	3	3	3	3	3	3	4	4
1700	4	5	5	5	6	6	6	7	7	8
1710	8	8	8	8	9	10	10	10	10	10
1720	10	11	13	13	14	14	15	15	15	15
1730	15	15	15	15	15	15	15	15	15	15
1740	15	16	16	16	16	16	16	16	17	17
1750	17	17	17	17	17	17	17	17	18	18
1760	18	18	18	18	18	18	18	18	19	21
1770	21	22	22	22	23	23	23	23	23	23
1780	23	23	23	23	23	23	23	23	23	23
1790	23	23	23	23	23	24	24	24	24	24
1800	25	25	26	27	27	27	27	27	27	27
1810	27	27	29	29	29	29	29	29	29	30
1820	30	30	30	30	30	30	30	30	31	31
1830	31	31	31	31	31	31	31	32	33	33
1840	33	33	33	33	33	33	33	33	33	32
1850	32	32	32	33	33	33	33	33	34	34
1860	34	34	34	34	34	34	34	34	34	34
1870	34	34	35	35	35	36	36	36	36	36
1880	37	37	37	37	37	37	37	37	37	37
1890	37	37	38	38	38	38	38	38	38	38
1900	38	38	38	38	38	38	38	38	38	37
1910	37	37	37	37	37	37	37	37	37	37
1920	37	37	37	37	37	37	37	37	37	37
1930	37	37	37	37	37	37	37	37	36	36
1940	36	37	37	37	37	37	37	37	37	37
1950	37	37	37	37	37	37	37	37	37	37
1960	37	37	37	37	37	37	37	37	37	37
1970	36	31	31	31	31	31	31	31	30	30
1980	30	30	30	30	30	30	30	30	30	30
1990	30	29								

Site and collection information (OKA)

Site name: Owaka **Site abbr.:** OKA
Country: New Zealand **State or Province:** South Island
Latitude: 46°23'S **Longitude:** 169°27'E **Altitude:** 305m
Species collected: *Libocedrus bidwillii*
Date of collection: 14 December 1977
Collectors: P. W. Dunwiddie, M. R. Boase
No. of trees/cores sampled (original): 14/54 **No. of discs:** 1

Site description:

Refer to LaMarche *et al.* (1979a) in detail.

This site is in a forest reserve west of the town of Owaka in eastern South Island. Clearcutting in the predominantly *Nothofagus menziesii* forest is common in this area. The road west from Owaka is followed 17 km to a junction with a road south to Chloris Pass, 3 km from the junction. Thirteen trees of *L. bidwillii* were cored at the pass on the west side of the road, where it enters Catlin Forest. Cedar Hill Scenic Reserve is on the opposite side of the road, with more *L. bidwillii* growing in it.

Disturbance appeared minimal in the area near the trees, which were emergent from the surrounding bush of *Leptospermum, Pseudowintera, Coprosma, Fuchsia* and *Nothofagus*. Trees were mature and up to 20 m tall, growing in moderately dense forest which gently sloped west and south from the Pass. Other collections included a single core from *Leptospermum ericoides* and a disc from *L. bidwillii* adjacent to a clearcut area nearby.

Summary of chronology statistics:

Chronology 1732 to 1976 (245 years) 14 trees 47 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	.9998	1.0011
Median	1.0037	1.0078	1.0059
Mean sensitivity	.1170	.1484	.1149
Standard deviation	.1727	.1290	.1677
Skewness	-.1715	-.9413	-.2538
Kurtosis	-.1740	1.6774	.1722
Autocorrelation order 1	.6473	-.0168	.6472
Partial autocorr order 2	.0530	-.1017	-.0293
Partial autocorr order 3	.1019	.0900	.1489
Variance due to autoregression	40.0%		41.5%
Error variance	.007335		.002427
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.3308

Common interval 1829 to 1975 (147 years) 10 trees 28 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.304	.383
Between trees (Y variance)	.285	.368
Within trees	.525	.560
Signal-to-noise ratio	3.982	5.817
Agreement with population chron	.799	.853
Variance in first eigenvector	34.82%	42.00%
Chron common interval mean	.998	.996
Chron common interval std dev	.188	.141

Chronology listings

Residual Chronology of OKA:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1734					915	876	859	1067	1070	1103
1740	1209	826	957	1171	1303	1209	939	864	1132	963
1750	832	1076	955	826	1065	1014	959	1121	1046	1025
1760	943	917	1069	970	933	884	1024	930	910	1100
1770	911	1019	1036	970	993	1034	925	1171	880	1050
1780	1120	1048	1040	937	1005	920	1063	879	1145	957
1790	931	886	1129	1067	805	1060	1116	1005	1003	1024
1800	1019	870	1180	1022	993	1034	972	989	1060	1000
1810	1128	1158	1122	1044	1021	1070	998	737	1048	1060
1820	1040	667	1093	1031	1071	1028	950	1066	1001	925
1830	653	1124	1000	888	866	1006	984	965	1058	960
1840	808	1116	933	1042	1180	1221	940	1045	955	922
1850	988	1131	984	953	648	1038	1047	1040	962	632
1860	967	1008	1036	1041	1071	945	1135	867	1144	1101
1870	1073	960	763	1091	1109	994	933	1150	1112	1005
1880	1014	1070	981	792	1201	1006	1078	899	1149	1004
1890	1137	945	1055	1264	1083	1180	977	825	1156	1107
1900	939	1047	907	969	793	1120	887	690	1116	807
1910	865	991	962	653	1034	1014	826	1251	1088	985
1920	911	1160	1056	964	631	1151	1229	939	1072	1126
1930	1008	896	1009	1135	936	764	1294	972	544	852
1940	1046	956	1127	993	1092	1119	1012	1202	1141	1115
1950	1024	1106	1069	1124	1033	905	540	1039	921	972
1960	1000	984	846	1226	1132	1041	975	1179	1088	1004
1970	814	858	971	934	904	881	957			

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1734					1	1	1	1	1	1
1740	1	1	1	1	1	1	1	1	1	2
1750	2	2	2	2	2	2	2	2	2	2
1760	2	2	2	2	3	3	3	5	5	5
1770	5	5	6	7	8	8	9	9	9	10
1780	10	11	11	11	12	12	12	13	13	14
1790	15	15	15	16	16	17	17	17	17	17
1800	19	20	22	22	23	23	24	25	27	27
1810	27	28	28	29	29	30	30	31	31	31
1820	31	31	31	31	31	31	31	32	33	34
1830	34	34	34	34	34	34	34	34	34	34
1840	34	34	34	34	34	34	34	34	34	34
1850	34	34	34	34	34	34	34	34	34	34
1860	34	34	34	34	34	34	34	34	34	34
1870	34	35	36	36	36	36	36	37	37	39
1880	39	39	39	39	39	39	39	39	39	40
1890	44	45	45	46	46	46	46	46	46	46
1900	46	46	46	46	46	47	47	47	47	47
1910	46	45	45	45	45	45	45	45	45	45
1920	45	44	44	44	44	44	44	44	44	44
1930	44	44	44	43	43	42	42	42	41	41
1940	41	41	41	41	41	41	41	41	41	41
1950	41	41	41	41	41	41	41	41	41	41
1960	41	41	41	41	41	41	41	41	41	41
1970	41	41	41	41	41	41	37			

Site and collection information (RUC)

Site name: Ruahine Corner **Site abbr.:** RUC
Country: New Zealand **State or Province:** North Island
Latitude: 39°38.2'S **Longitude:** 176°10.7'E **Altitude:** 1200m
Species collected: *Libocedrus bidwillii*
Date of collection: 28-29 January 1993
Collector(s): L. Xiong, J. G. Palmer, B. E. Smith; G. Rogers
No. of trees/cores sampled: 30/81 **No. of discs:** 0

Site description:

This site is located in the Ruahine Range. The site is very close to Ruahine Corner Hut. Access was by helicopter. The site consists of two subsites. One subsite was just South-East of the Hut. There were six trees over 1 m at DBH and 21 trees were sampled from this subsite. Another subsite is about 400 m North-west of the Hut. There was a large grass area (burnt several years ago) between the subsite and the Hut. Nine trees were sampled from this subsite.

Summary of chronology statistics:

Chronology 1473 to 1991 (519 years) 29 trees 73 radii

Chronology type	STNDRD	RESID (AR 2)	ARSTAN
Mean	1.0000	1.0000	.9940
Median	.9953	.9995	.9849
Mean sensitivity	.1230	.1541	.1222
Standard deviation	.2046	.1450	.1902
Skewness	.1633	.3658	.3752
Kurtosis	1.3350	2.5510	1.9340
Autocorrelation order 1	.6778	.0104	.6346
Partial autocorr order 2	.0134	-.0253	.0162
Partial autocorr order 3	-.0227	-.0395	-.0447
Variance due to autoregression	41.3%		37.1%
Error variance	.006010		.005054
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.8409

Common interval 1764 to 1960 (197 years) 24 trees 50 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.295	.332
Between trees (Y variance)	.290	.328
Within trees	.471	.455
Signal-to-noise ratio	9.791	11.719
Agreement with population chron	.907	.921
Variance in first eigenvector	32.18%	35.21%
Chron common interval mean	1.009	1.003
Chron common interval std dev	.189	.138

Chronology listings

Residual Chronology of RUC:

	Tree-Ring Indices										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1475						894	888	830	960	1098						1	1	1	1	1
1480	971	1015	1187	1024	698	925	1028	1383	1782	901	1	1	1	1	1	1	2	2	2	2
1490	726	952	918	1178	881	1065	474	1089	924	1039	2	2	2	2	2	2	2	2	2	2
1500	975	897	1027	1217	1071	1148	1303	1231	943	896	2	2	2	2	2	2	2	2	2	2
1510	1174	996	891	1103	886	1123	749	1160	1198	784	2	2	3	3	3	3	3	3	3	4
1520	985	757	1100	1332	947	1078	1026	753	1020	933	4	4	4	4	4	4	4	4	4	4
1530	981	1013	1175	1165	1423	840	928	770	1205	1263	4	4	4	4	4	4	4	4	4	4
1540	1001	953	925	616	843	864	875	1119	1015	983	4	4	4	4	4	4	4	4	4	4
1550	1044	1070	1050	1125	893	793	872	854	962	1038	4	4	4	4	4	4	4	4	4	4
1560	1103	1334	1116	1171	747	994	862	954	850	824	4	4	4	4	5	5	5	5	5	5
1570	1217	866	901	1299	1089	836	895	1036	780	950	5	5	5	5	5	5	5	5	5	5
1580	1139	718	790	1054	813	886	1033	1104	1023	995	5	5	5	5	5	5	5	5	5	5
1590	1024	1102	1016	921	949	1151	1178	1560	961	804	5	5	5	5	5	5	5	5	5	5
1600	615	1174	1019	1022	559	1011	1035	998	1024	955	5	5	5	5	5	5	5	5	5	5
1610	920	1095	1128	1124	1018	1011	966	1139	941	1150	6	6	6	8	8	8	8	8	8	8
1620	1006	1106	938	989	836	1045	1137	795	1031	1152	8	8	8	8	8	8	8	8	8	9
1630	842	940	1028	877	1044	942	910	978	904	892	9	10	10	10	11	11	11	11	11	11
1640	966	1021	1112	1082	1038	992	1000	1106	1021	1112	11	12	12	12	12	13	13	13	14	14
1650	1013	1049	705	931	642	947	966	943	928	926	14	14	14	14	15	15	15	15	15	15
1660	921	980	1007	1002	912	895	1133	1038	1054	1074	16	18	19	20	20	20	20	20	21	21
1670	812	1277	1195	840	1001	891	996	1135	764	991	21	23	23	23	23	23	23	24	24	25
1680	1023	986	922	1104	990	1070	914	1068	1235	1113	25	26	27	27	28	28	29	29	29	29
1690	1081	1122	1037	1058	961	925	958	897	944	943	29	29	29	30	30	31	32	34	34	34
1700	922	1036	1085	1118	904	934	1452	999	771	978	34	35	36	36	36	36	36	36	36	37
1710	847	1104	1169	918	1019	990	943	904	886	1072	39	39	39	39	40	41	41	41	41	41
1720	1090	1018	878	1013	1163	1108	1028	994	1359	650	41	41	41	42	42	42	43	44	44	45
1730	1160	839	801	978	1035	992	1180	924	944	1025	45	45	46	47	47	47	48	48	49	49
1740	1142	592	1022	1147	812	1011	891	969	1061	1012	49	50	50	50	50	50	50	50	50	50
1750	948	1123	746	995	1004	1027	968	1047	947	1000	50	50	50	50	50	50	51	52	53	53
1760	1142	1000	991	958	946	907	1237	848	865	1100	53	53	55	57	57	58	58	58	58	58
1770	865	915	1014	998	949	1012	958	1201	1056	1038	58	59	59	59	60	60	60	60	60	60
1780	1027	1016	844	1092	1012	1055	1097	917	956	1025	60	60	60	60	61	62	63	63	63	64
1790	997	874	855	1085	946	1006	1173	1302	847	1274	64	64	64	64	64	64	64	64	65	65
1800	1186	1187	1033	788	1224	999	978	1060	988	886	65	65	66	66	66	66	66	66	66	66
1810	947	1162	1095	913	1138	1117	936	885	1151	1036	66	67	68	68	68	69	69	69	69	69
1820	879	1129	1006	1047	1073	1333	777	1132	985	1080	69	69	69	69	69	69	69	69	69	69
1830	715	1039	883	775	1051	1010	967	1023	975	1024	69	70	70	70	70	71	71	71	71	71
1840	861	1177	951	951	891	1027	858	709	1036	885	71	71	71	71	71	71	71	71	71	71
1850	1083	1038	1099	1017	893	948	1013	1027	902	1023	71	69	69	69	69	69	69	69	69	69
1860	926	1489	1083	1176	1045	758	1285	853	1085	993	69	69	69	69	69	69	69	69	69	69
1870	917	1082	670	1034	1025	922	956	890	991	1127	69	69	69	69	69	69	69	69	69	69
1880	1041	1032	951	698	927	1100	1019	904	881	1065	69	70	70	70	70	70	70	70	70	70
1890	962	1052	1088	1096	987	1031	1269	982	1099	1053	70	70	70	70	70	70	70	70	70	70
1900	1085	1074	847	1042	1066	1033	897	755	1187	1209	70	69	69	69	69	69	69	69	69	69
1910	802	890	863	1186	1082	1171	787	1205	870	1002	69	69	69	69	69	69	69	69	69	69
1920	981	1203	954	998	694	860	1048	902	911	938	69	68	68	68	68	68	68	68	68	68
1930	804	1171	1372	1226	1347	649	982	1159	697	747	68	67	67	67	67	67	67	67	67	67
1940	945	858	920	1034	1124	905	967	1038	907	967	67	66	66	66	66	66	66	66	66	66
1950	1075	1091	969	991	904	977	1045	1178	1093	1106	66	64	64	64	64	64	64	64	64	64
1960	975	909	910	979	949	1026	947	1213	896	1119	64	61	61	61	61	61	61	61	61	61
1970	1012	977	1076	1197	1022	857	1019	1044	906	1029	61	60	60	60	60	60	55	55	55	55
1980	1118	947	957	1050	970	858	891	1141	962	1261	55	52	52	52	52	52	52	51	50	50
1990	953	1086									50	49								

Site and collection information (RUH)

Site name: Rahu Saddle **Site abbr.:** RUH
Country: New Zealand **State or Province:** South Island
Latitude: 42°18.95'S **Longitude:** 172°07'E **Altitude:** 672m
Species collected: *Libocedrus bidwillii*
Date of collection: 8 August 1992, 9 October 1992, 9 December 1993
Collector(s): L. Xiong, J. G. Palmer, B. E. Smith
No. of trees/cores sampled: 25/47 **No. of discs:** 1

Site description:

Rahu Saddle is located at west of Spring Junction and a few kilometres west of the main divide in a broad glaciated pass through the Southern ALPs. Most of the stand is poorly drained as reflected by an extensive cover of *Sphagnum* moss. The major trees are *Libocedrus bidwillii* and *Nothofagus solandri var. cliffortioides* and the less abundand *N. menziesii*. Numerous *Phyllocladus alpinus* and *Myrsine divaricata* are also present but most are overtopped and do not exceed 15 cm dbh. *Libocedrus bidwillii* generally has narrow, compact crowns. Some individuals have cuts at the base from wood cutters, and several have been felled. *Libocedrus bidwillii* seedlings are not aboudant relative to those of the other main canopy species but are adequate to assure establishment of numerous saplings and small stems. Tree were cored on both sides of the road at the pass. Data-logger and dendrobands have been installed in this site for two years Please refer to LaMarche (1979a), Veblen & Stewart (1982) for more information about this site.

Summary of chronology statistics:

Chronology 1560 to 1991 (432 years) 20 trees 40 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	1.0000	1.0323
Median	.9423	.9951	1.0046
Mean sensitivity	.1592	.1957	.1560
Standard deviation	.4202	.1953	.4073
Skewness	5.0135	1.0497	5.5165
Kurtosis	37.2575	11.8473	51.1330
Autocorrelation order 1	.7332	.0160	.7605
Partial autocorr order 2	.1559	-.0843	-.2355
Partial autocorr order 3	.1160	-.0001	.0581
Variance due to autoregression	45.7%		47.1%
Error variance	.012177		.012201
Ratio of error variance of chronologies (ARSTAN/STNDRD)			1.0019

Common interval 1784 to 1950 (167 years) 14 trees 28 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.277	.273
Between trees (Y variance)	.263	.261
Within trees	.504	.463
Signal-to-noise ratio	4.999	4.949
Agreement with population chron	.833	.832
Variance in first eigenvector	31.30%	30.41%
Chron common interval mean	.980	1.010
Chron common interval std dev	.230	.145

Chronology listings

Residual Chronology of RUH:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1563				2612	701	489	655	647	1126	1186
1570	340	162	583	780	836	805	1322	1247	966	709
1580	811	1241	994	1117	1017	583	1343	960	1451	1724
1590	828	1073	1072	883	1132	980	1062	1061	939	1165
1600	944	1290	393	1034	1061	603	680	1017	1184	841
1610	1130	831	1062	1060	827	1147	576	1176	885	980
1620	979	955	721	1125	1071	763	774	974	1143	1010
1630	867	950	998	761	1116	1071	1405	775	809	934
1640	1221	1351	1208	1023	868	992	956	989	753	975
1650	1166	1286	608	1098	874	1014	946	849	906	982
1660	943	1030	1020	1068	1068	1032	1074	906	1186	724
1670	1003	1526	999	785	1083	1165	1067	985	701	926
1680	1047	1262	723	988	1108	1113	887	839	1170	1064
1690	1043	816	1066	1154	1154	948	913	743	1092	947
1700	920	1001	849	991	947	966	1006	674	1025	1104
1710	837	1155	975	798	1044	1016	1151	955	789	1204
1720	1092	863	878	1241	1161	988	903	1267	1544	541
1730	1074	801	974	1145	1270	1041	916	784	940	1215
1740	985	703	1216	1012	984	1542	1086	1092	1068	894
1750	876	1358	741	852	991	1045	886	931	900	982
1760	1274	1022	1134	1174	1170	991	1176	913	916	1112
1770	507	1103	819	967	914	1026	817	1266	972	982
1780	1044	1124	1088	1103	773	1018	973	863	822	1162
1790	908	976	1087	976	931	940	899	1109	1029	961
1800	1094	770	1029	1026	1302	1198	723	946	1362	1100
1810	1036	1025	1171	963	993	1200	999	890	1144	939
1820	981	926	988	953	1110	1087	611	1215	1193	912
1830	882	1074	852	849	937	1037	1123	1045	942	995
1840	865	1126	939	1075	1042	1156	996	972	1092	809
1850	1119	984	1044	1062	839	941	1033	1199	954	874
1860	1280	1078	978	984	1024	996	1092	793	1041	935
1870	917	873	783	940	1192	1062	987	1259	1094	1195
1880	814	881	922	973	1096	898	1112	915	1168	1127
1890	1022	998	1211	1085	864	1158	1279	919	1110	1162
1900	1056	1039	872	983	690	948	1078	705	880	746
1910	820	940	926	1098	1093	1081	725	1086	978	1087
1920	1060	1119	1043	1137	1024	1001	1272	1203	726	987
1930	938	1119	1461	1222	1059	503	1030	1013	676	960
1940	1154	1162	1006	1056	1196	1172	1099	891	1147	1164
1950	1018	667	1089	792	971	816	799	988	963	980
1960	1101	892	947	1101	955	1015	963	962	939	917
1970	979	881	1080	986	1191	958	1077	1157	860	1027
1980	884	958	1109	1103	1146	938	1000	1218	1017	1334
1990	959	964								

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1563				1	1	1	1	1	1	1
1570	1	1	1	1	1	1	1	2	2	3
1580	3	3	3	3	3	3	3	3	3	3
1590	3	3	3	3	3	3	3	3	3	3
1600	3	3	3	3	3	4	4	4	4	4
1610	4	4	4	4	4	4	4	5	5	5
1620	6	6	6	6	6	6	6	6	6	6
1630	6	6	6	6	6	6	6	6	6	6
1640	6	6	6	6	6	6	6	6	6	6
1650	7	7	7	7	8	9	9	9	9	9
1660	9	9	10	10	10	10	10	10	10	10
1670	10	10	10	10	10	10	10	11	11	11
1680	11	11	11	11	11	11	11	11	11	11
1690	11	11	11	11	12	12	13	13	13	14
1700	14	16	16	16	16	16	16	16	16	17
1710	18	18	18	18	18	18	18	19	20	20
1720	20	21	22	22	22	23	23	23	23	23
1730	23	23	23	23	23	23	23	23	23	23
1740	23	23	23	23	23	23	23	23	23	23
1750	25	26	26	27	27	27	27	27	27	27
1760	29	29	30	30	30	31	31	31	31	31
1770	31	31	31	31	31	31	32	32	32	32
1780	33	33	33	34	35	35	36	36	36	36
1790	36	36	36	36	36	36	36	36	36	36
1800	37	37	37	37	37	37	37	37	37	37
1810	37	37	37	37	37	37	38	38	38	38
1820	38	38	38	38	38	38	38	38	38	38
1830	38	38	38	38	39	39	39	39	39	39
1840	39	39	39	39	39	39	39	39	39	39
1850	39	39	39	39	39	38	38	38	38	38
1860	38	38	38	38	38	38	38	38	38	37
1870	37	37	37	37	37	37	37	37	37	37
1880	37	34	34	34	34	34	33	33	33	33
1890	33	33	33	33	33	33	33	33	33	33
1900	33	33	33	34	34	34	34	34	34	34
1910	34	34	34	34	34	34	34	34	34	34
1920	34	34	34	34	34	33	33	33	33	33
1930	33	33	33	33	33	33	33	33	33	33
1940	33	33	33	33	33	33	33	33	33	33
1950	33	31	30	29	29	29	29	29	29	29
1960	29	29	29	29	29	29	28	28	28	28
1970	28	28	28	28	28	28	27	27	27	27
1980	27	27	26	25	24	24	24	24	23	18
1990	16	13								

Site and collection information (STR)

Site name: Stratford Side (East Egmont) **Site abbr.:** STR
Country: New Zealand **State or Province:** North Island
Latitude: 39°18.5'S **Longitude:** 174°07.25'E **Altitude:** 860m
Species collected: *Libocedrus bidwillii*
2Date of collection: 31 December 1991
Collector(s): J. O. Murphy
No. of trees/cores sampled: 7/11 **No. of discs:** 0

Site description:

No description was recorded for this site.

Summary of chronology statistics:

Chronology 1626 to 1990 (365 years) 7 trees 11 radii

Chronology type	STNDRD	RESID (AR 2)	ARSTAN
Mean	1.0000	1.0000	1.0016
Median	.9904	1.0052	1.0105
Mean sensitivity	.1454	.1755	.1400
Standard deviation	.2335	.1690	.2389
Skewness	.3702	.7260	.1475
Kurtosis	2.0280	4.9663	1.3885
Autocorrelation order 1	.6292	-.0178	.6903
Partial autocorr order 2	.1974	.0587	.1453
Partial autocorr order 3	.0426	.0789	-.0073
Variance due to autoregression	43.7%		52.5%
Error variance	.009396		.010087
Ratio of error variance of chronologies (ARSTAN/STNDRD)			1.0735

Common interval 1742 to 1950 (209 years) 4 trees 6 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.334	.290
Between trees (Y variance)	.310	.278
Within trees	.486	.369
Signal-to-noise ratio	1.801	1.543
Agreement with population chron	.643	.607
Variance in first eigenvector	45.14%	41.60%
Chron common interval mean	.995	1.001
Chron common interval std dev	.218	.143

Chronology listings

Residual Chronology of STR:

	Tree-Ring Indices										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1629										1224										1
1630	1507	588	2081	925	813	1042	678	782	1455	889	1	1	1	1	1	1	1	1	1	1
1640	1149	992	904	831	999	1069	1109	754	849	695	1	1	1	1	1	1	1	1	1	1
1650	1135	1005	594	810	891	1203	897	818	885	1094	1	1	1	1	1	1	1	1	1	1
1660	927	909	837	820	1104	999	1119	1026	1115	1138	2	2	2	2	2	3	3	3	3	3
1670	982	1095	1030	870	1006	773	899	1009	1086	1135	3	3	4	4	4	4	4	4	4	4
1680	835	1064	767	1005	1004	851	813	1273	1148	868	4	4	4	4	4	4	4	4	5	5
1690	1057	1005	1093	935	976	1129	845	1138	1090	893	5	5	5	5	5	5	5	5	5	6
1700	1127	1013	1134	1202	1077	1050	1508	908	872	898	6	6	6	6	6	6	6	6	6	6
1710	853	905	1085	962	1121	988	1060	1017	921	943	6	6	7	7	7	7	7	7	7	7
1720	918	950	882	933	776	1042	997	1018	1444	921	7	7	7	7	7	7	7	7	7	7
1730	1157	697	1167	943	1135	1037	1253	932	1051	1176	7	7	7	7	7	7	7	7	7	7
1740	924	586	954	688	712	703	849	880	1033	1140	7	8	8	8	8	8	8	8	8	8
1750	975	1023	830	1145	1142	919	1203	1130	1138	1031	8	8	8	8	8	8	8	8	8	8
1760	1015	1034	997	993	900	841	1132	983	916	910	8	8	8	8	8	8	8	8	8	8
1770	828	945	1030	1033	1020	1063	1068	1099	1071	1238	8	8	8	8	8	8	8	8	8	8
1780	1040	808	959	1056	1096	996	1156	961	979	1205	8	8	8	8	8	8	8	8	8	8
1790	870	996	913	878	1040	1131	897	1226	1005	1187	8	8	8	8	8	8	8	8	8	8
1800	1097	1142	758	816	1297	1117	1056	1021	981	1040	8	8	8	8	9	9	9	9	9	9
1810	973	957	1147	856	867	1066	930	794	996	1027	9	9	9	9	9	9	10	10	10	11
1820	941	1151	962	906	1134	989	860	1033	1019	919	11	11	11	11	11	11	11	11	11	11
1830	667	1070	902	884	1196	1007	1062	1166	997	998	11	11	11	11	11	11	11	11	11	11
1840	902	1284	938	1032	739	1096	999	920	1158	885	11	11	11	11	11	11	11	11	11	11
1850	1049	1012	984	1024	705	953	1205	1032	1008	1132	10	10	10	10	10	10	10	10	10	10
1860	901	1034	1267	1070	1060	933	1091	1085	1077	1106	10	10	10	10	10	10	10	10	10	10
1870	833	1024	818	990	1082	915	1179	1093	1075	1116	10	10	10	10	10	10	10	10	10	10
1880	995	1193	1275	598	950	1247	1100	862	1066	944	9	9	9	9	9	9	9	9	9	9
1890	1183	1280	1041	1214	1110	975	1052	1045	1166	995	9	9	9	9	9	9	9	9	9	9
1900	882	1016	815	822	747	895	957	786	1040	927	9	9	9	9	9	9	9	9	9	9
1910	721	1008	792	882	1029	1154	816	1077	856	1070	9	9	9	9	9	9	9	9	9	9
1920	902	1072	1025	1173	694	831	1098	964	887	955	9	9	9	9	9	9	9	9	9	9
1930	910	1261	1176	1148	1150	442	1089	1010	727	774	9	9	9	9	9	9	9	9	9	9
1940	1209	1252	1149	1209	1042	1021	856	971	888	1032	9	9	9	9	9	9	9	9	9	9
1950	1152	1098	1185	589	791	903	979	940	977	871	9	8	8	8	8	7	7	6	6	6
1960	1057	1249	989	1100	1096	1025	905	1093	645	858	4	3	3	3	3	3	3	3	3	3
1970	768	856	980	1170	1288	1118	1032	950	914	769	3	3	3	3	3	3	3	3	3	3
1980	1178	925	1205	1617	1035	762	945	1336	727	1190	3	3	3	3	3	3	3	3	3	3
1990	693										3									

Site and collection information (TKP)

Site name: Takapari **Site abbr.:** TKP
Country: New Zealand **State or Province:** North Island
Latitude: 40°05'S **Longitude:** 176°00'E **Altitude:** 838m
Species collected: *Libocedrus bidwillii*
Date of original collection: 13 January 1978
Original collectors: P. W. Dunwiddie, M. R. Boase
No. of trees/cores sampled (original): 16/60 **No. of discs:** 0
Date of new collection: 12 February 1994
New collectors: L. Xiong, B. E. Smith
No. of trees/cores sampled (new): 15/29 **No. of discs:** 0

Site description:

Please refer to LaMarche (1979a) about the original collection information.

Libocedrus bidwillii is abundant in nearly pure stands in some areas of the Ruahine Range. This site was cored in one such area in the central part of the range. Takapari Road takes off from the main road, which follows along the Pohangina River north of Ashhurst. This road, which is referred to by the Forest Service as the Delaware Ridge Road, runs east into the range about 3 km south of the bridge near Piripiri.

The site, 11 km up this road, is on a level area in a very open, wet stand. The understory is composed primarily of mosses, grasses, and the shrub *Pseudowintera colorata*. A few small *L. bidwillii* are found, but almost no saplings. Trees tend to have full, healthy crowns, reach heights of 15 m, and diameters of 80 cm.

Takapari Road takes off from the main road, which follows along the Pohangina River north of Ashhurst. The site, from 9 to 11 km up this road, is on a level area in a very open, wet stand. *Libocedrus bidwillii* is the predominant species, pink pine and shrub species *Pseudowintera colorata* are the another two major species at this sites. *Libocedrus bidwillii* are very abundant with different diameters from 20 to 65cm and there are also some dead trees at this site. We could not relocate the original trees. Pink pine was also collected from this site. Dead and dying *Libocedrus* are abundant at this site.

Summary of chronology statistics:

Chronology 1256 to 1992 (737 years) 31 trees 63 radii

Chronology type	STNDRD	RESID (AR 2)	ARSTAN
Mean	1.0000	1.0000	1.0020
Median	.9768	.9952	.9877
Mean sensitivity	.1351	.1758	.1326
Standard deviation	.2530	.1568	.2380
Skewness	.3785	.0188	.3460
Kurtosis	.0145	1.3509	.0498
Autocorrelation order 1	.7699	-.0257	.7410
Partial autocorr order 2	.0590	.0328	.1834
Partial autocorr order 3	-.0394	.0309	-.0158
Variance due to autoregression	59.0%		56.6%
Error variance	.007651		.006449
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.8429

Common interval 1723 to 1903 (181 years) 25 trees 39 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.361	.385
Between trees (Y variance)	.356	.381
Within trees	.577	.581
Signal-to-noise ratio	13.842	15.408
Agreement with population chron	.933	.939
Variance in first eigenvector	39.82%	40.74%

Chron common interval mean	1.011	1.006
Chron common interval std dev	.225	.147

Chronology listings

Residual Chronology of TKP:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1258									1338	1302
1260	965	1102	660	1126	958	839	982	832	905	1010
1270	1099	860	1105	939	919	814	1123	1309	776	859
1280	728	1033	763	990	899	1107	996	1197	1115	1306
1290	942	691	1201	1096	921	997	1343	1222	596	1256
1300	1049	990	1337	1074	670	1249	1041	1126	907	1120
1310	960	1042	1123	859	856	1055	1018	858	897	940
1320	1042	935	1058	923	884	854	771	1102	982	970
1330	962	891	864	1005	935	635	951	1207	961	1271
1340	735	1199	915	1089	1087	1154	854	898	791	987
1350	961	751	912	908	991	913	877	830	1123	934
1360	899	792	1157	1289	1216	633	994	923	926	943
1370	1126	1282	1205	1005	984	1129	1791	929	1174	844
1380	842	1578	894	1034	1073	796	1222	1157	1003	1223
1390	820	985	829	983	875	937	775	1020	1385	1063
1400	1129	1179	1116	992	1023	1182	892	1001	1281	907
1410	870	852	1033	903	871	1264	711	982	964	824
1420	990	939	1159	740	1084	1026	1007	775	900	807
1430	902	921	1033	1109	975	1043	883	1051	903	1146
1440	966	855	890	858	927	845	1064	841	981	1154
1450	953	1225	674	934	805	967	927	1065	1141	1266
1460	600	943	965	1130	950	1090	1083	1006	927	957
1470	926	855	993	1057	1170	1439	1062	692	881	940
1480	1278	1040	1134	1327	764	1066	1071	749	872	1167
1490	1000	1063	1208	940	1069	1297	937	1033	946	920
1500	1065	1057	1021	930	1018	897	1027	920	1189	973
1510	1018	1031	833	1055	733	975	1183	904	949	868
1520	1078	1180	1112	1119	1061	779	1069	1036	889	950
1530	1112	965	917	927	989	1015	1055	1390	642	995
1540	1181	1105	959	1008	926	1205	768	1139	1014	1167
1550	1043	1223	424	861	1157	925	837	919	815	1300
1560	1045	1009	949	1041	973	922	748	1047	1260	1184
1570	1288	1226	1018	1069	1092	1199	665	839	995	724
1580	924	993	840	1193	1279	1198	1224	1328	972	894
1590	1012	1018	945	1087	892	848	936	865	898	969
1600	976	977	451	913	965	1030	940	953	941	939
1610	1163	1018	1049	1207	1017	1108	973	1261	867	1158
1620	900	1023	567	1016	1087	846	1112	1133	991	1072
1630	1009	1054	1098	639	868	1021	1196	865	971	1023
1640	1059	1108	1080	882	896	901	930	1193	983	1209
1650	980	846	641	811	919	940	1045	894	1126	1059
1660	927	1079	768	903	854	975	1052	1315	1114	1253
1670	899	1183	1000	860	921	1003	1091	1163	692	1045
1680	956	1052	735	1081	896	1106	1004	1028	1079	1153
1690	1216	923	891	1200	905	1072	887	953	1119	964
1700	1050	981	1101	1163	890	1029	1410	943	904	1048
1710	958	1220	1327	816	1178	1190	855	891	949	896
1720	923	999	854	972	883	991	834	989	1330	741
1730	1312	937	1089	954	1025	1085	1195	856	1109	1063
1740	922	544	961	1100	858	1043	847	854	1056	1078
1750	864	1030	781	958	979	1004	931	1022	861	962
1760	1007	994	942	1010	934	965	1190	863	957	1169
1770	807	1057	1129	1069	1019	1036	775	1131	1172	1211
1780	1098	826	829	1012	920	988	1106	986	1006	1242
1790	1087	961	878	1172	937	1119	1093	1171	724	1073
1800	1179	1180	958	833	1108	1226	957	1002	1118	885
1810	999	941	962	969	1186	1191	926	779	1040	985
1820	923	1097	1026	963	1083	1348	707	1225	1031	1041
1830	563	982	807	771	995	1073	1105	1092	960	1098
1840	811	1207	885	850	934	949	918	732	1004	1012
1850	1022	1000	1034	967	914	1055	969	1030	872	1051
1860	974	1102	854	1142	1115	622	1119	1003	1198	1032
1870	1168	1055	693	1229	1127	1085	1322	1016	868	1257
1880	955	1052	985	573	924	1142	894	822	894	1181
1890	1160	1228	1106	1148	969	1032	1215	998	1104	1109
1900	1215	1227	810	1087	697	900	985	734	876	885
1910	947	1165	855	1083	991	1180	491	1215	697	917
1920	1052	1280	1005	1207	1118	889	1072	745	953	1178
1930	819	1086	1040	999	1010	597	982	1081	908	797
1940	848	941	966	950	1038	891	793	1040	828	969
1950	1132	1059	1002	878	924	1032	889	876	937	1125
1960	1062	1026	1016	966	954	1065	993	1119	726	1162
1970	1060	1046	1195	1166	1061	948	1072	1282	1155	849
1980	999	965	1017	1139	961	1103	1191	1225	1111	1177
1990	883	1020	916							

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1258									1	1
1260	1	1	1	1	1	1	1	1	2	2
1270	2	3	3	3	3	3	3	3	3	3
1280	3	3	3	3	3	3	3	3	3	3
1290	3	3	3	3	3	3	3	3	3	3
1300	3	3	3	3	3	4	4	4	4	4
1310	4	4	4	4	4	4	4	4	4	4
1320	4	4	4	4	4	4	4	4	4	4
1330	4	4	4	4	4	4	4	4	4	4
1340	4	4	4	4	4	4	4	4	4	4
1350	4	4	4	4	4	4	4	4	4	4
1360	4	4	4	4	4	4	5	5	5	5
1370	5	5	5	5	5	5	5	6	6	6
1380	6	6	6	6	6	6	6	6	6	6
1390	6	6	6	6	6	6	6	6	6	6
1400	6	6	6	6	6	6	6	6	6	6
1410	6	6	6	6	6	6	6	6	6	6
1420	6	6	7	7	7	7	7	7	8	8
1430	8	8	8	9	9	9	9	9	9	9
1440	9	9	9	9	9	9	9	9	9	9
1450	9	9	9	9	9	9	10	10	10	10
1460	10	13	13	13	13	13	13	13	13	13
1470	13	13	13	14	15	15	15	15	15	15
1480	15	15	15	15	15	15	15	15	15	15
1490	15	15	15	15	16	16	16	17	17	18
1500	18	19	19	19	19	19	19	19	19	19
1510	19	19	19	19	19	19	19	19	19	19
1520	19	19	19	19	19	19	19	19	19	20
1530	20	20	20	19	19	19	19	19	19	19
1540	20	20	20	20	20	20	20	20	20	20
1550	20	20	20	20	19	19	19	19	19	19
1560	19	19	19	19	19	19	19	19	19	19
1570	19	19	19	19	19	19	19	18	18	18
1580	18	18	18	18	18	18	18	18	18	18
1590	19	18	18	18	19	19	19	19	19	19
1600	19	19	19	19	19	19	19	19	19	19
1610	19	19	19	19	19	19	19	19	19	19
1620	19	19	19	19	19	20	20	20	20	20
1630	21	21	21	21	21	21	21	21	21	22
1640	22	22	22	24	24	25	25	25	25	25
1650	25	25	25	25	25	25	25	25	25	25
1660	26	27	27	28	28	28	28	28	28	28
1670	30	30	31	32	32	32	32	32	32	33
1680	33	33	33	33	33	33	33	34	34	34
1690	34	34	35	35	36	36	36	36	36	36
1700	36	36	36	37	37	37	38	38	38	38
1710	38	38	38	40	40	40	40	40	40	40
1720	40	40	40	41	41	41	41	41	41	42
1730	42	42	42	42	42	42	42	42	42	42
1740	42	42	42	42	43	43	43	43	43	43
1750	43	43	43	43	44	44	45	45	45	45
1760	45	45	47	47	48	48	48	48	48	48
1770	48	48	48	48	49	50	51	51	52	52
1780	53	53	54	54	54	54	54	54	54	54
1790	54	54	54	54	54	54	54	54	54	54
1800	54	54	54	54	54	54	54	54	54	54
1810	54	54	54	54	54	54	54	54	54	54
1820	54	54	54	53	53	53	53	53	53	53
1830	53	53	53	53	53	53	53	53	54	54
1840	54	54	54	54	54	54	54	54	54	54
1850	54	54	54	54	54	54	54	54	54	54
1860	54	53	53	53	53	53	53	53	53	53
1870	53	53	53	53	53	53	53	53	53	53
1880	53	53	53	53	53	53	53	53	53	53
1890	53	53	53	53	53	53	53	53	53	53
1900	53	54	54	54	51	50	49	47	46	46
1910	46	46	46	46	46	44	42	42	41	41
1920	41	40	40	40	40	40	40	40	39	39
1930	39	38	38	38	37	30	28	28	25	25
1940	24	23	23	22	22	22	22	22	22	22
1950	22	21	21	21	20	20	19	19	19	19
1960	19	19	19	19	19	19	19	19	19	18
1970	18	18	18	18	18	18	18	8	8	8
1980	8	8	8	8	8	8	8	7	7	6
1990	5	5	5							

Chronology listings

Residual Chronology of TOA:

	Tree-Ring Indices										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1513				878	719	1266	822	928	1144	895				1	1	1	1	1	1	1
1520	1056	1055	997	1346	798	710	1115	998	708	1083	1	1	1	1	1	1	2	2	2	2
1530	857	1217	921	763	626	818	1142	1205	997	872	2	2	2	2	2	2	2	2	2	2
1540	1149	954	832	876	745	1010	1189	1010	1008	1210	2	2	2	2	2	2	2	2	2	2
1550	821	1170	783	754	1080	953	874	1077	944	1044	2	2	2	2	2	2	3	3	3	3
1560	986	1054	813	832	717	1380	1234	839	1128	762	3	3	3	3	3	3	3	3	3	3
1570	894	1117	887	879	1253	1398	1500	919	832	1107	3	3	3	3	3	3	3	3	3	3
1580	1186	897	1065	989	930	1213	1008	1271	909	870	3	4	5	5	5	6	6	6	6	6
1590	853	819	1008	1232	932	965	816	805	916	963	6	6	6	6	6	6	6	6	7	7
1600	856	888	889	1049	1106	959	1152	1025	922	791	7	7	7	7	7	7	7	7	7	7
1610	1256	1304	752	949	842	957	831	886	844	824	7	7	7	7	7	8	9	9	10	10
1620	902	881	910	922	1114	907	1126	989	929	1164	10	10	10	10	11	11	11	11	11	11
1630	1034	950	1085	820	865	1107	1028	926	957	1017	11	11	11	11	12	12	12	12	12	12
1640	1018	1021	1103	1022	1075	1087	926	1207	1008	989	13	13	13	13	13	13	13	13	15	15
1650	1125	1062	769	1073	969	918	1085	1033	1077	802	16	16	18	18	18	19	20	20	20	20
1660	892	967	937	1082	987	1040	960	958	1160	1141	20	20	20	20	20	20	20	20	20	20
1670	921	1439	1136	940	1003	960	1002	1169	730	1094	20	20	20	20	20	20	20	20	20	20
1680	990	1052	826	1143	997	998	797	1058	1077	1122	20	20	20	20	20	21	22	22	22	22
1690	1012	1188	1112	1422	915	914	883	950	1035	932	22	22	22	23	23	23	23	23	23	23
1700	950	1033	1006	1117	906	974	1336	897	827	961	23	23	23	23	23	23	23	23	23	23
1710	958	1247	1316	1006	1160	1053	1092	851	869	1242	23	23	24	25	26	27	27	27	27	27
1720	1096	1092	842	1001	1148	1147	880	1025	1293	812	27	27	27	27	27	27	28	28	28	28
1730	1135	773	901	1070	970	1067	1035	836	1034	1100	28	28	28	28	29	29	29	29	29	29
1740	1006	676	1005	1130	873	1122	890	1055	1028	1050	29	29	30	30	30	30	30	31	31	31
1750	968	989	694	1089	938	1062	955	1074	851	1086	32	32	33	33	33	33	33	33	33	33
1760	1393	1200	1121	1068	1000	784	1131	880	1022	1315	33	33	34	34	34	34	34	34	34	34
1770	728	1169	1100	912	941	1085	983	1088	986	840	34	34	34	34	34	34	35	35	35	35
1780	977	978	811	979	941	945	1029	958	1041	1086	35	36	36	36	36	36	36	36	36	36
1790	921	879	876	1025	906	1087	1046	1037	888	1166	37	38	39	39	39	39	39	39	39	39
1800	1139	923	1040	822	1274	1328	848	970	946	947	39	41	41	41	41	41	41	41	41	42
1810	840	1178	990	919	969	1210	1063	980	1024	1035	42	42	42	42	42	42	42	42	42	42
1820	859	972	1019	1100	982	1243	821	1216	1091	1066	42	42	42	42	42	42	42	42	42	42
1830	613	848	937	764	994	941	958	1017	985	969	42	42	42	42	42	42	42	42	42	42
1840	911	1263	978	962	991	1094	815	856	1123	998	42	42	42	42	42	42	42	42	42	42
1850	1088	1031	920	1034	891	881	1032	887	823	1030	42	42	42	42	42	42	42	42	42	42
1860	1219	1541	1010	1087	1045	937	1122	707	1059	1115	42	42	42	42	42	42	42	42	42	42
1870	970	1034	649	1152	1105	923	986	998	991	1107	42	42	42	42	42	42	42	42	42	42
1880	913	962	873	817	807	930	1090	990	981	1153	42	42	42	42	42	42	42	42	42	42
1890	1050	936	1155	848	971	900	1377	1099	1091	1196	42	42	43	43	43	43	43	43	43	43
1900	1143	1081	904	1100	748	1050	1114	680	974	1123	43	43	43	43	43	43	43	43	43	43
1910	860	919	800	1092	1256	1201	670	1298	919	1208	43	43	43	43	43	43	43	43	43	43
1920	942	1475	1050	1207	595	812	1109	917	909	893	43	43	43	43	43	43	43	43	43	43
1930	879	1304	1371	1254	1202	509	992	1149	648	1031	43	43	43	43	43	43	43	43	43	43
1940	1363	929	906	1098	1024	858	866	1110	864	909	43	43	43	43	43	43	43	43	43	43
1950	1142	904	964	1046	772	894	896	1086	992	1140	43	43	43	43	42	42	42	42	42	42
1960	1007	992	816	1129	962	937	956	1139	835	1062	41	41	41	41	41	41	41	41	41	41
1970	937	1078	988	1215	931	980	1115	981	941	991	41	41	41	41	41	41	40	40	40	40
1980	956	1019	1055	1169	875	1069	892	1187	819	1235	40	39	39	39	39	39	39	39	38	38
1990	961	1016	966	752							38	38	38	1						

Site and collection information (TOB)

Site name: Site B, Hauhungatahi, Tongariro **Site abbr.:** TOB
Country: New Zealand **State or Province:** North Island
Latitude: 39°14'S **Longitude:** 175°26'E **Altitude:** 1100m
Species collected: *Libocedrus bidwillii*
Date of collection: 8 November 1993
Collector(s): L. Xiong, J. G. Palmer, B. E. Smith
No. of trees/cores sampled: 19/40 **No. of discs:** 0

Site description:

Site B was 60m lower than site A which situated in and outside of Dr John Ogden's 1100 m site. There are about 24 species at this zone. This zone includes all the five canopy species at site A plus another canopy species *Weinmannia racemosa*. All other 18 species include 12 small tree species, 3 shrub species, 2 liane species and 1 tree fern species. The detailed vegetation description refer to Druitt *et al.* (1990).

Summary of chronology statistics:

Chronology 1332 to 1992 (661 years) 15 trees 27 radii

Chronology type	STNDRD	RESID (AR 3)	ARSTAN
Mean	1.0000	1.0000	.9972
Median	.9739	.9973	.9776
Mean sensitivity	.1425	.1875	.1424
Standard deviation	.2458	.1720	.2350
Skewness	.6330	-.0474	.5866
Kurtosis	.6989	1.5445	.6457
Autocorrelation order 1	.7075	.0052	.6790
Partial autocorr order 2	.1008	-.0472	.0810
Partial autocorr order 3	.0156	.0189	-.0413
Variance due to autoregression	.0%		.0%
Error variance	.000000		.000000
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.0000

Common interval 1708 to 1990 (283 years) 9 trees 15 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.342	.392
Between trees (Y variance)	.323	.378
Within trees	.657	.612
Signal-to-noise ratio	4.286	5.476
Agreement with population chron	.811	.846
Variance in first eigenvector	39.09%	43.39%
Chron common interval mean	.998	.997
Chron common interval std dev	.215	.158

Chronology listings

Residual Chronology of TOB:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1333				977	819	847	1186	914	773	1203
1340	867	1010	710	1005	1084	895	1543	1115	594	1093
1350	1043	1379	1016	962	999	1602	1503	1131	1234	655
1360	924	1323	1159	610	986	1056	992	404	965	1250
1370	1127	878	935	946	939	1082	1237	950	796	1135
1380	1402	859	1019	1315	775	901	1544	786	1468	682
1390	997	1502	1037	1019	1239	1315	1006	836	793	1053
1400	1182	927	1104	861	1057	924	1433	1271	382	794
1410	1082	852	1027	882	933	843	1006	1104	703	915
1420	1248	863	864	816	956	835	1341	986	965	1217
1430	1085	900	903	978	997	1109	904	1198	1063	1131
1440	1093	1013	1097	979	987	708	792	941	1015	799
1450	817	1124	1014	1001	955	992	868	1070	1120	810
1460	972	1005	1004	786	1189	1080	908	992	935	942
1470	864	864	869	895	929	865	698	942	916	1031
1480	892	1234	979	1163	1087	1220	1175	850	834	1261
1490	891	1474	1116	1128	799	889	681	1066	877	910
1500	1038	1241	967	964	1241	1214	804	970	834	925
1510	957	923	849	1039	790	976	1097	998	1070	1060
1520	807	1060	1193	1065	1082	927	1052	1006	933	869
1530	958	1068	891	919	913	989	1173	1097	1122	895
1540	1010	1148	622	761	834	990	964	1040	1033	1171
1550	1272	1228	823	706	938	1097	1007	925	885	1104
1560	1169	1078	976	872	1002	992	905	675	963	966
1570	859	1279	1082	1112	1150	1073	856	884	1089	803
1580	989	929	1074	981	1077	963	1034	1128	967	984
1590	1041	929	1011	1281	1029	1072	944	851	885	1071
1600	1018	984	668	852	1049	1103	1090	949	955	918
1610	1253	639	790	937	839	1058	936	1112	970	1130
1620	1055	1085	477	983	1071	784	1223	1317	849	1227
1630	1153	1181	1238	730	922	1122	1262	653	1006	1017
1640	1179	1543	1233	1027	1014	1113	946	1277	1015	1073
1650	955	861	398	1058	978	985	1001	979	1080	1033
1660	1052	946	603	945	908	889	921	923	1115	1262
1670	967	1394	1090	715	970	1080	1091	1220	444	1117
1680	1017	992	524	1052	1008	960	990	966	1118	1318
1690	1123	1004	1045	1173	911	1016	974	1007	1170	1002
1700	1089	1116	1020	1286	916	804	1213	844	906	881
1710	981	1230	1233	890	1216	994	1035	760	1006	1082
1720	1064	1069	798	934	892	1084	945	1142	1278	894
1730	1201	545	866	1058	937	1115	1206	822	979	1103
1740	970	548	1026	1144	849	976	842	1009	1071	1110
1750	935	1028	560	948	900	1028	909	996	855	1072
1760	1095	1187	951	1114	886	874	890	917	923	1156
1770	719	1129	1088	1033	1012	1201	887	1136	964	962
1780	941	865	760	1084	995	945	1022	1018	948	1027
1790	1083	914	876	1069	993	1123	875	1076	967	1358
1800	1360	1169	1171	590	1276	1541	918	931	938	1011
1810	874	1087	891	938	1004	1117	975	923	1015	941
1820	864	1015	996	1086	975	1276	935	1290	1080	1071
1830	511	1008	914	792	971	949	1029	1008	1049	1015
1840	914	1301	996	946	845	1134	759	670	1097	860
1850	959	1082	1077	1120	913	1014	1020	1013	876	1083
1860	884	1375	1201	1208	963	916	1196	759	1043	1035
1870	1021	1051	571	1096	1080	1032	1102	1004	934	1019
1880	968	976	921	786	911	1055	968	986	910	1111
1890	1099	1029	1137	1059	924	841	1316	1118	1227	1322
1900	1203	1105	870	960	695	1047	1021	645	944	1079
1910	812	1059	844	1051	1201	1121	623	1447	760	1164
1920	865	1231	1039	950	730	850	1137	873	844	945
1930	793	1164	1321	1150	1081	474	963	1146	835	723
1940	1042	922	1020	1039	1042	877	920	1258	985	952
1950	1322	1086	1062	967	772	939	984	1134	1066	1086
1960	1119	1001	823	1203	992	929	928	1034	841	1093
1970	833	922	1067	1121	952	973	1051	1026	726	892
1980	1010	915	1014	1085	972	1070	900	1134	784	1257
1990	996	978	1111							

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1333				1	1	1	1	1	1	1
1340	1	1	1	1	1	1	1	1	1	1
1350	1	1	2	2	2	2	2	2	2	2
1360	2	2	2	2	2	2	2	2	2	2
1370	2	2	2	2	2	2	2	2	2	2
1380	2	2	2	2	2	2	2	2	2	2
1390	2	2	2	2	2	2	2	2	2	2
1400	2	2	2	2	2	2	2	2	2	2
1410	2	2	2	2	2	2	2	2	2	2
1420	2	2	2	2	2	2	2	2	2	2
1430	2	2	2	2	2	2	2	2	2	2
1440	2	2	3	3	3	3	3	4	5	5
1450	5	5	5	5	5	5	5	5	5	5
1460	5	5	5	5	5	5	5	5	5	5
1470	5	5	5	5	5	5	5	5	5	5
1480	5	5	6	6	6	6	6	6	6	6
1490	6	6	6	6	6	6	6	6	6	6
1500	6	6	6	6	6	6	6	6	6	6
1510	6	6	6	6	6	6	6	6	6	6
1520	6	7	8	8	8	8	9	9	9	9
1530	9	9	9	9	9	9	9	9	9	9
1540	9	9	9	9	9	9	9	9	9	9
1550	9	9	9	9	9	9	9	9	9	9
1560	9	9	9	9	9	9	9	10	10	10
1570	10	11	11	11	11	11	11	11	11	12
1580	12	12	13	13	13	13	13	13	13	13
1590	13	13	13	13	13	13	14	14	14	14
1600	14	15	15	15	15	15	15	15	15	15
1610	15	15	15	15	15	15	15	15	15	15
1620	15	15	15	15	16	16	16	16	16	16
1630	16	16	16	16	16	16	16	16	16	16
1640	16	16	16	16	16	16	16	16	17	17
1650	17	17	17	17	17	18	18	18	18	18
1660	18	18	18	18	18	18	18	18	18	18
1670	18	18	18	18	18	18	18	18	18	18
1680	19	19	19	19	19	19	19	19	19	20
1690	20	20	20	20	20	20	20	20	20	20
1700	20	20	20	20	20	20	20	21	21	21
1710	21	21	21	21	21	21	21	21	21	21
1720	21	21	21	21	21	21	21	21	21	21
1730	21	21	21	21	21	21	21	21	21	21
1740	21	21	21	21	21	21	21	21	21	21
1750	21	21	21	21	21	21	21	21	21	21
1760	21	21	21	21	21	21	21	21	21	21
1770	21	21	21	21	21	21	21	21	21	21
1780	21	21	21	21	22	22	22	22	22	22
1790	22	22	22	22	22	22	22	22	22	22
1800	23	21	21	21	21	22	22	22	22	22
1810	22	22	22	22	23	23	23	23	23	23
1820	23	23	23	23	23	23	23	23	23	23
1830	23	23	23	23	23	23	23	23	23	23
1840	23	23	23	23	23	23	23	23	23	23
1850	24	23	23	23	23	23	23	23	23	23
1860	23	23	23	23	23	23	23	23	23	23
1870	23	22	22	22	22	22	22	22	22	22
1880	22	22	22	22	22	21	21	21	21	21
1890	21	21	21	21	21	21	21	21	21	21
1900	21	21	21	21	21	21	21	21	21	21
1910	21	21	21	21	21	21	21	21	21	21
1920	21	21	21	21	21	21	21	21	21	21
1930	21	21	21	21	21	21	21	21	21	21
1940	21	21	21	21	21	21	21	21	21	21
1950	21	21	21	21	21	21	21	21	21	21
1960	21	21	21	21	21	21	21	21	21	21
1970	21	20	20	20	20	20	20	20	20	20
1980	20	20	20	20	20	20	20	20	20	20
1990	20	19	19							

Site and collection information (TOC)

Site name: Site C, Hauhungatahi, Tongariro **Site abbr.:** TOC
Country: New Zealand **State or Province:** North Island
Latitude: 39°14'S **Longitude:** 175°26'E **Altitude:** 1000m
Species collected: *Libocedrus bidwillii*
Date of collection: 9 November 1993, 10 February 1994
Collector(s): L. Xiong, J. G. Palmer, B. E. Smith
No. of trees/cores sampled: 18/40 **No. of discs:** 0

Site description:

Site C was sampled in and outside of Dr John Ogden's 1000 m site. There were 10 canopy tree species, 12 small tree species, 2 shrub species, 4 liane and 1 tree fern species at this zone. The forest dominanted by three gymnosperms *Phyllocladus alpinus, Podocarpus hallii* and *Libocedrus bidwillii*. Species such as *Dacrydium cupressinum, Podocarpus spicatus*, and *Nestegis cunninghamii* all reached their upper limits at about 1000m above which *Dacrydium biforme* and *Phyllocladus alpinus* were found for the first time. The detailed vegetation description refer to Druitt *et al.* (1990).

Summary of chronology statistics:

Chronology 1213 to 1992 (780 years) 14 trees 25 radii

Chronology type	STNDRD	RESID (AR 2)	ARSTAN
Mean	1.0000	1.0000	.9977
Median	.9729	.9954	.9765
Mean sensitivity	.1509	.1866	.1428
Standard deviation	.2623	.1843	.2349
Skewness	1.3490	1.3703	1.5185
Kurtosis	5.0431	11.6262	6.7507
Autocorrelation order 1	.6699	-.0526	.6027
Partial autocorr order 2	.1198	.0779	.1873
Partial autocorr order 3	-.0636	-.0143	-.1056
Variance due to autoregression	.0%		.0%
Error variance	.000000		.000000
Ratio of error variance of chronologies		(ARSTAN/STNDRD)	.0000

Common interval 1553 to 1870 (318 years) 10 trees 14 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.224	.262
Between trees (Y variance)	.217	.257
Within trees	.394	.376
Signal-to-noise ratio	2.766	3.454
Agreement with population chron	.734	.775
Variance in first eigenvector	28.55%	31.83%
Chron common interval mean	.994	1.001
Chron common interval std dev	.204	.148

Chronology listings

Residual Chronology of TOC:

	Tree-Ring Indices										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1214					864	1061	985	719	1097	866					1	1	1	1	1	1
1220	719	922	2447	641	2541	957	846	789	518	865	1	1	1	1	1	1	1	1	1	1
1230	970	886	1035	1010	785	882	829	851	842	1247	1	1	1	1	1	1	1	1	1	1
1240	1089	1057	1686	897	1123	1182	1074	701	671	835	1	1	1	1	1	1	1	1	1	1
1250	1142	1188	865	539	925	1220	763	863	1199	855	1	1	1	1	1	1	1	1	1	1
1260	1190	1193	1173	767	1432	1430	967	966	1196	796	1	1	1	1	1	1	1	2	2	2
1270	705	899	1207	969	1271	797	958	978	1365	1085	2	2	3	3	3	3	3	3	3	3
1280	1055	681	933	1095	1249	1763	1296	1059	719	1219	3	3	3	3	3	3	3	3	3	3
1290	772	1316	780	828	844	773	1072	975	1030	1167	3	3	3	3	3	3	3	3	3	3
1300	889	1044	1116	720	903	941	1190	1126	915	976	3	3	3	3	3	3	3	3	3	3
1310	816	1191	834	906	907	969	820	1313	1060	1030	3	3	3	2	2	2	2	2	2	2
1320	985	1081	975	947	759	1099	1050	858	762	1052	2	3	3	3	3	3	3	3	3	3
1330	864	1187	927	1341	1006	865	1034	844	1086	1468	3	3	3	3	3	3	3	3	3	3
1340	809	954	878	844	959	1008	886	852	1136	880	3	3	3	3	3	3	3	3	3	3
1350	830	934	985	1030	1271	1363	1197	925	950	1161	3	3	3	3	3	3	3	3	4	4
1360	1161	453	799	775	1576	420	1100	1158	964	784	4	4	4	4	4	5	5	5	5	5
1370	1123	1079	1096	882	961	1081	936	992	1193	978	5	5	5	5	5	5	5	5	5	5
1380	1043	1218	844	931	1060	688	967	861	892	941	5	5	6	6	6	6	6	6	6	6
1390	1011	942	843	1022	1115	857	928	1104	1288	1219	6	6	6	6	6	6	6	6	6	6
1400	1437	948	1350	1438	1270	1475	520	925	1002	700	6	6	7	7	7	7	7	7	7	7
1410	974	898	936	880	1093	1007	935	885	1074	900	7	7	7	7	7	7	7	7	7	7
1420	849	1037	1160	831	996	1039	1054	840	905	828	7	7	7	7	7	7	7	7	7	7
1430	1074	1070	1183	1117	773	1046	973	1150	1010	1204	7	7	8	8	8	8	8	8	8	8
1440	1057	756	953	897	785	767	1128	914	1041	1037	8	8	8	8	8	8	8	8	8	8
1450	924	778	750	873	1091	985	981	1111	1061	948	8	8	8	8	8	8	8	8	8	8
1460	921	1219	1220	1032	1072	1031	729	920	860	888	8	8	8	8	8	8	8	8	8	8
1470	801	1013	882	1026	862	1006	1091	1033	1030	1124	8	8	8	8	8	8	8	8	8	8
1480	1284	900	691	1097	950	931	1098	897	921	1090	8	8	8	8	8	8	8	8	8	8
1490	1323	986	995	1025	640	1187	1037	1015	965	1088	8	8	8	8	8	8	8	8	9	9
1500	955	1086	973	892	1031	894	1063	1186	1138	1042	9	9	9	9	9	9	10	10	10	10
1510	1100	1276	864	777	978	1204	846	915	1009	1075	10	10	10	10	10	10	11	11	11	11
1520	945	1009	1283	986	904	831	987	926	869	887	11	11	11	11	11	11	11	11	11	12
1530	985	907	835	964	966	1001	1017	1267	840	1030	12	12	12	12	12	12	12	13	14	14
1540	961	901	862	847	950	1121	938	952	944	1197	14	14	14	14	14	14	14	14	14	14
1550	1037	1268	355	998	1062	1133	887	1050	891	1161	14	14	14	15	15	15	15	15	15	15
1560	1103	943	1022	1069	970	1070	813	965	878	941	15	15	15	15	15	15	15	15	15	15
1570	925	1029	954	1107	1026	984	814	895	1118	787	15	15	15	15	15	15	15	15	15	15
1580	854	960	1010	1093	1071	986	1196	1099	982	984	15	15	15	15	15	15	16	16	16	16
1590	969	988	1142	1141	865	1041	860	811	886	890	16	16	16	16	16	16	16	16	16	16
1600	991	1018	801	755	926	962	964	918	1055	1001	16	16	16	16	16	16	16	16	16	16
1610	1219	623	880	1111	1003	1005	953	1088	996	1132	16	16	16	16	16	16	16	16	16	16
1620	989	1077	532	863	1047	1010	1093	1167	1050	1209	16	16	17	17	17	17	17	17	17	17
1630	950	1126	1044	772	952	1038	1228	962	1079	894	17	17	17	17	17	17	17	17	17	17
1640	1255	1221	1168	899	939	1005	1036	1260	1154	959	17	17	17	17	17	17	17	17	17	17
1650	902	1048	600	1193	1098	1016	1191	1085	1018	990	17	17	17	17	17	17	17	17	17	17
1660	979	1181	696	1057	886	1045	1172	1144	1095	1171	17	17	18	18	18	18	18	18	18	18
1670	890	1349	1053	704	1127	995	1058	1115	722	1125	18	18	18	18	18	18	18	18	18	18
1680	1011	1028	554	1115	1047	1057	1025	1295	1083	1209	18	18	18	18	18	18	18	18	18	18
1690	1307	827	994	1101	871	990	974	1028	1100	928	18	18	18	18	18	18	18	18	18	18
1700	1083	1099	1075	1377	917	840	1248	764	759	899	18	18	18	19	19	19	19	19	19	19
1710	1029	1148	1171	809	1248	1124	984	568	931	949	19	19	19	19	19	19	19	19	19	19
1720	1001	973	807	1051	1068	1171	1003	1174	1332	829	19	19	19	19	19	19	19	19	19	19
1730	1253	408	884	942	910	1134	1213	743	1064	1103	19	19	19	19	19	19	19	19	19	19
1740	939	578	1086	1058	824	1020	816	931	1129	1144	19	19	19	19	19	19	19	19	19	19
1750	979	1071	533	964	1005	969	905	1043	909	1079	20	20	20	20	20	20	20	20	20	20
1760	1046	1173	1089	1010	1028	672	1080	881	950	1077	20	20	20	20	20	20	20	20	20	20
1770	695	1070	1031	1076	983	1033	855	993	958	941	20	20	20	20	20	20	20	20	20	20
1780	1024	907	959	1005	895	977	1105	1018	938	1089	20	20	20	20	20	20	20	20	20	20
1790	1034	947	941	1084	908	1160	845	1165	890	1341	20	20	20	20	20	20	20	20	20	20
1800	1176	1186	1093	782	1228	1240	807	913	977	1004	20	20	20	20	20	20	20	20	20	20
1810	795	994	968	955	1052	1039	957	910	1066	1008	20	19	19	19	19	20	20	20	20	20
1820	926	1091	954	1065	1109	1166	867	1208	1034	954	20	20	20	20	20	20	20	20	20	20
1830	613	1026	948	771	936	954	974	985	1053	976	20	20	20	20	20	20	20	20	20	20
1840	854	1085	995	1006	906	1135	809	909	1146	949	20	20	20	20	21	21	21	21	21	21
1850	992	1089	1034	1015	773	948	1074	1019	944	1075	21	21	21	21	21	21	21	21	21	21
1860	903	1129	1106	1207	1274	728	1369	815	1114	1039	21	22	22	22	22	22	22	22	22	22
1870	994	995	636	1216	1135	1169	1299	1126	794	948	22	21	21	21	21	21	22	22	22	22
1880	941	1005	985	763	925	1102	1021	1076	928	1001	22	22	22	22	22	22	22	22	22	22
1890	1078	1109	1008	976	1086	1071	1356	978	1095	1114	22	20	20	19	19	19	19	19	19	19
1900	1195	1073	775	1034	765	1094	1082	660	1074	998	19	19	19	19	19	19	19	19	18	18
1910	740	986	951	1014	1117	1277	644	1230	829	1157	18	18	18	18	18	18	18	18	18	18
1920	855	1258	982	966	619	920	1142	905	919	1092	18	18	17	17	17	17	17	17	17	17
1930	918	1238	1169	1122	1121	508	985	1137	666	794	17	17	17	17	17	17	17	17	17	17
1940	904	1023	1103	1299	1062	1024	890	1046	909	1017	17	17	17	17	17	17	17	17	17	17
1950	1020	994	877	1048	888	967	969	939	1044	1004	17	17	17	17	17	17	17	17	17	17
1960	1050	917	933	1132	932	995	926	1199	919	990	17	17	17	17	17	17	17	17	17	17
1970	833	1033	921	917	903	849	1126	1163	1114	1167	17	14	14	13	13	13	13	13	13	12
1980	960	646	1169	1242	973	883	1065	1657	677	1020	12	11	11	11	10	10	10	9	9	9
1990	816	914	1159								9	8	8							

Site and collection information (TRK)

Site name: Tarkus Knob
Site abbr.: TRK
Country: New Zealand
State or Province: South Island
Latitude: 43°05'S **Longitude:** 170°58'E **Altitude:** a. 900m b.925m
Species collected: *Libocedrus bidwillii*
Date of collection: January 1980
Collectors: D. A. Norton; A. E. Moore
No. of trees/cores sampled (original): 80/127 **No. of discs:** 0
Site description:

Refer to Norton (1983a) in detail.

This site is located in the Cropp River catchment, a tributary of the Whitcombe and Hokitika Rivers. Access was by helicopter; foot access from the Hokitika River road end (35 km south of Hokitika township) takes 2 days. The site consists of two subsites.

The Tarkus Knob (unofficial name) subsite is located opposite the New Zealand Forest Service Cropp hut on the true left-hand side of Cropp River. The site is located on the steep slopes above the river flats. The forest is dominated by *Olearia colensoi*, *O. lacunosa*, *Dracophyllum longifolium*, *Coprosma pseudocuneata* with emergent *Dracophyllum traversii* and *Libocedrus bidwillii*.

The Danger Gully subsite is on the true right-hand side of Danger Gully about 0.5 km up the Cropp River from Tarkus Knob. The are sampled is on the Northeast side of the spur separating the Cropp River and Danger Gully. The closed canopy at 2-3 m is dominated by *Archeria traversii*, *Dracophyllum longifolium* and *D. traversii* with *Libocedrus bidwillii* emergent above this.

Summary of chronology statistics:

Chronology 1526 to 1978 (453 years) 21 trees 27 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	1.0000	.9987
Median	1.0030	.9974	1.0010
Mean sensitivity	.1763	.2113	.1717
Standard deviation	.2350	.1858	.2146
Skewness	-.0313	-.1501	.0037
Kurtosis	1.9686	1.1971	1.5691
Autocorrelation order 1	.5761	-.0557	.5041
Partial autocorr order 2	.0740	-.0266	-.0072
Partial autocorr order 3	-.0321	-.0640	-.0390
Variance due to autoregression	39.5%		30.4%
Error variance	.011442		.008036
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.7023

Common interval 1807 to 1957 (151 years) 14 trees 16 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.253	.286
Between trees (Y variance)	.249	.281
Within trees	.492	.569
Signal-to-noise ratio	4.645	5.474
Agreement with population chron	.823	.846
Variance in first eigenvector	30.90%	34.20%
Chron common interval mean	.996	.995
Chron common interval std dev	.182	.152

Chronology listings

Residual Chronology of TRK:

	Tree-Ring Indices										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1528									1386	562									1	1
1530	1365	955	1767	877	588	882	1112	987	1044	894	1	1	1	1	1	1	1	1	1	1
1540	793	1061	739	1336	796	890	1131	1187	712	1396	1	1	1	1	1	2	2	2	2	2
1550	1049	402	1225	952	1020	804	1234	1186	721	995	2	2	2	2	2	2	2	2	2	3
1560	1057	1033	1079	960	744	898	804	1383	1122	1272	3	3	3	3	3	3	3	3	3	3
1570	1229	983	1080	973	755	1132	1149	1034	990	1259	3	4	4	4	4	4	4	4	4	4
1580	1105	847	938	1022	1166	1359	1156	1137	999	948	4	4	4	4	4	4	4	4	4	4
1590	947	1065	1129	1113	881	991	694	844	879	1298	4	4	4	4	4	4	4	4	4	4
1600	914	777	1130	1172	1078	1098	617	944	1154	1070	4	4	4	4	4	4	4	4	4	4
1610	908	747	958	1129	757	1067	400	1151	1113	973	4	4	4	4	4	4	4	4	4	4
1620	988	894	893	1128	971	728	1206	1310	1216	886	4	4	4	4	4	4	4	4	4	4
1630	1095	837	1344	1170	454	748	1188	1236	1323	898	4	4	4	4	4	4	4	4	4	4
1640	1139	1215	913	1054	1099	1008	732	835	696	1162	4	4	4	4	4	4	4	4	4	4
1650	967	833	486	1090	1068	1022	1041	857	902	1066	4	4	4	4	4	4	4	4	4	4
1660	985	1066	1129	863	943	975	1086	762	1168	712	4	4	4	4	4	5	5	5	5	5
1670	674	1169	908	1141	1210	907	1172	721	1070	1134	5	5	5	5	5	5	5	5	5	5
1680	849	1107	962	1205	983	1156	895	843	1201	893	5	6	6	6	6	6	6	6	6	6
1690	1144	979	770	1204	1087	1006	1006	1081	1074	1086	6	7	7	7	7	7	7	7	7	7
1700	994	1321	567	1516	1110	885	1326	655	703	1060	7	7	7	7	7	7	7	7	7	7
1710	853	984	962	1111	1437	1063	1096	562	302	699	7	7	7	7	8	8	8	8	8	8
1720	963	836	935	883	929	1054	802	946	1203	817	8	8	8	8	8	8	8	8	8	8
1730	1097	881	1065	1019	846	1276	1150	800	1012	1102	8	8	8	8	8	8	8	8	8	8
1740	1021	1045	1346	1029	1412	1307	1400	1102	1372	911	8	8	8	8	8	8	8	9	9	9
1750	613	1114	834	1360	911	983	824	1224	832	1151	9	9	9	9	9	9	9	9	9	9
1760	930	1000	1021	892	1010	884	1042	1205	1018	952	9	9	9	9	9	9	9	9	9	9
1770	713	1162	814	1019	813	929	912	1089	1032	1105	9	10	10	10	10	11	11	11	11	11
1780	1010	986	868	1043	1006	1069	1228	952	1152	1304	11	11	11	11	12	12	12	12	12	13
1790	832	794	1026	859	888	938	1048	972	907	537	13	13	13	13	13	13	14	14	14	15
1800	1291	941	1202	798	1200	1383	668	728	997	890	15	15	15	15	15	15	15	16	16	16
1810	1034	901	1124	958	1060	1043	1044	753	911	1034	16	16	16	16	16	16	16	16	16	16
1820	1000	921	993	1092	989	1088	770	1309	969	884	16	16	16	16	16	16	16	16	16	16
1830	926	1076	666	811	1135	1076	1220	860	961	948	17	17	17	17	17	17	17	17	18	18
1840	1288	1379	997	885	666	1241	976	1050	984	796	18	18	18	18	18	18	20	20	20	21
1850	918	992	973	947	1080	1167	919	950	831	836	21	21	21	21	21	21	21	21	21	22
1860	1001	1213	886	987	1148	1007	992	898	1015	1072	22	22	22	22	22	22	22	23	23	23
1870	1139	973	859	1243	1064	1127	827	1086	548	1386	23	23	23	23	23	23	23	24	24	25
1880	1170	1137	954	930	1056	1190	1184	940	937	1098	25	25	25	25	25	25	25	25	25	25
1890	1043	1005	1206	1092	791	619	1373	994	839	1073	25	25	25	25	25	25	25	25	25	25
1900	1046	869	962	815	1002	869	977	992	1158	977	26	26	26	26	26	26	26	26	26	26
1910	993	983	912	1226	910	1003	1018	1270	932	834	26	26	26	26	26	26	26	26	26	26
1920	1035	1072	919	668	1188	952	976	1097	870	862	26	26	26	26	26	26	26	26	26	26
1930	879	1074	1103	933	1058	586	792	851	794	929	26	26	26	26	26	26	26	26	26	26
1940	1269	1135	1003	1009	1007	888	915	977	1113	889	26	26	26	26	26	26	26	26	26	26
1950	1114	893	1186	1264	1110	1080	986	843	703	1076	26	26	26	26	26	26	26	26	25	25
1960	1251	1005	991	944	853	910	965	1073	983	891	25	25	25	25	25	25	24	24	24	24
1970	1104	1015	1167	1081	989	906	1150	1073	913		24	23	23	23	23	23	23	23	23	

Site and collection information (UWR)

Site name: Urewera **Site abbr.:** UWR
Country: New Zealand **State or Province:** North Island
Latitude: 38°40.7'S **Longitude:** 177°11.8'E **Altitude:** 854m
Species collected: *Libocedrus bidwillii*
Date of original collection: 28 January 1978
Original collectors: P. W. Dunwiddie, M. R. Boase
No. of trees/cores sampled (original): 14/56 **No. of discs:** 0
Date of new collection: 6-7 February 1994
New collectors: L. Xiong, J. G. Palmer, B. E. Smith
No. of trees/cores sampled (new): 20/51 **No. of discs:** 0

Site description:

Refer to LaMarche (1979a) about the original collection information.

The site is 2 km north of Sandy Bay on the slopes immediately southeast of Kaipo Lagoon in Urewera National Park. *Libocedrus bidwillii*, 22-25 m tall, are scattered in a predominantly *Nothofagus menziesii* forest on a 15, west-northwest facing slope. They appear to be remnants of an earlier successional stage, as they are somewhat emergent from the dense *Nothofagus* canopy, and no trees under 50 cm dbh were found. All trees cored were northeast of where the trail enters the "Lagoon", a boggy depression opening in the forest. An understory of *Myrsine divaricata* and *Phyllocladus alpinus* was present on the moderately drained slope. Disturbance appeared minimal. Two cores were also collected from a single *Dacrydium colensoi* growing in the lagoon.

We have resampled this site in 1994. It was impossible to locate the original trees.

Summary of chronology statistics:

Chronology 1140 to 1992 (853 years) 34 trees 68 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	.9976	1.0001
Median	.9982	1.0041	.9922
Mean sensitivity	.1705	.1900	.1689
Standard deviation	.2466	.1642	.2403
Skewness	.5398	-.1698	.6548
Kurtosis	1.4593	.5364	2.2968
Autocorrelation order 1	.6053	-.0045	.5917
Partial autocorr order 2	.0385	-.1071	-.0480
Partial autocorr order 3	.0249	-.0358	.0251
Variance due to autoregression	35.7%		27.4%
Error variance	.007940		.005478
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.6900

Common interval 1508 to 1740 (233 years) 18 trees 27 radii

Mean correlations:	Detrended series	Residuals (white noise)
Among all radii	.234	.353
Between trees (Y variance)	.229	.349
Within trees	.423	.491
Signal-to-noise ratio	5.334	9.639
Agreement with population chron	.842	.906
Variance in first eigenvector	27.92%	38.75%
Chron common interval mean	.998	.999
Chron common interval std dev	.202	.152

Chronology listings

Residual Chronology of UWR:

Tree-Ring Indices

Date	0	1	2	3	4	5	6	7	8	9
1142			1199	1042	938	1283	1037	823	952	1471
1150	1114	1142	714	1251	1257	1134	1613	808	1212	629
1160	1211	754	1005	608	780	582	759	842	821	1300
1170	729	1148	1309	761	1367	748	1008	709	1058	1818
1180	1246	1273	1102	1153	685	1069	953	630	1015	859
1190	1126	1878	1020	557	814	671	638	956	639	967
1200	892	1169	1151	797	484	1116	972	1034	715	641
1210	885	663	1330	1603	1100	906	1270	1039	864	1302
1220	992	1022	1331	2205	674	805	977	1038	555	907
1230	930	676	1056	929	761	1232	647	1337	769	1026
1240	712	898	702	1382	769	1047	1432	1646	906	1303
1250	1561	1247	1184	1102	716	1669	1566	1017	755	963
1260	747	906	821	885	731	898	1090	1326	1363	985
1270	1045	1005	748	1096	1015	1135	688	1202	1085	1050
1280	900	1112	978	870	1246	1040	964	1394	878	759
1290	933	711	733	912	778	694	1126	1468	674	730
1300	879	923	856	845	942	1087	1165	899	1640	1293
1310	843	844	1188	1060	1029	639	802	1056	1053	990
1320	1257	993	842	877	1012	902	1265	1215	1293	935
1330	1103	1095	1106	1398	998	737	668	1090	1041	1403
1340	498	888	804	848	1230	1429	720	787	924	932
1350	795	1112	1132	1261	869	709	1015	914	800	1045
1360	962	948	924	1063	1144	933	989	984	1043	907
1370	973	1043	863	1058	1365	935	694	869	1228	1150
1380	857	874	895	789	807	1070	1185	1068	989	1279
1390	1276	1366	1075	974	915	904	851	1029	970	860
1400	1046	799	912	1066	1151	674	724	972	959	1104
1410	1049	898	970	948	781	990	866	816	954	1042
1420	862	985	803	975	1152	845	883	1048	1121	962
1430	1095	1260	857	967	795	1233	1068	1132	848	1068
1440	1157	903	1004	1063	975	940	1090	1172	1068	1285
1450	1012	973	1011	1081	1086	1009	1098	1107	969	1306
1460	708	1071	1102	977	909	987	838	929	937	1102
1470	931	1073	737	1181	934	811	1071	1037	1086	879
1480	1032	767	886	1135	809	1031	963	590	1040	1391
1490	970	771	849	1230	879	1188	1070	1013	1205	865
1500	1029	861	1141	969	1068	1062	1032	858	1005	851
1510	950	1203	715	1102	989	1040	1103	1041	1037	1077
1520	981	950	850	1074	852	1134	1065	812	788	1129
1530	1194	1007	979	1263	996	1270	1220	1120	568	1005
1540	1009	785	995	1190	964	1083	1009	928	826	1174
1550	1070	1150	758	1060	1052	1017	852	1058	936	1270
1560	1039	1156	897	919	1054	1136	609	787	915	904
1570	917	1168	989	1160	992	1045	958	1024	998	1022
1580	1053	970	1045	935	939	852	1050	995	959	903
1590	973	930	990	955	863	1075	903	1007	807	917
1600	942	1125	537	871	1165	1089	1052	1365	1049	1382
1610	1222	1038	987	990	1130	1138	852	1099	919	1282
1620	941	961	694	1020	1041	776	679	1193	915	1335
1630	1105	943	878	932	1179	993	1027	725	1004	955
1640	751	876	1045	823	864	1092	1209	1358	1079	876
1650	942	1071	852	1029	980	1008	1078	782	1119	1017
1660	1034	1038	688	1028	1026	1033	897	1084	1048	919
1670	917	1123	973	899	902	945	901	806	904	1248
1680	1451	1107	829	1278	866	1053	884	689	880	997
1690	860	1036	1007	1074	1189	1262	713	1042	1031	900
1700	1147	1000	977	1318	965	1000	1098	1036	1063	766
1710	918	1122	977	998	1121	909	1048	1103	999	1286
1720	957	1017	932	1056	562	972	1202	927	1212	869
1730	1112	825	919	1278	994	594	1196	1105	798	1048
1740	936	511	962	1114	929	1135	1044	1205	1033	1402
1750	1140	866	527	1028	1191	998	901	1066	1059	1217
1760	1229	1072	807	1017	896	740	1001	821	985	1073
1770	1009	689	963	1014	945	1090	892	1118	983	1282
1780	990	668	977	1057	1059	922	971	877	1010	986
1790	1033	1176	1014	1037	874	858	903	1052	923	1147
1800	1047	1133	1045	924	1343	763	1086	1206	1182	1066
1810	1001	874	1008	1094	1039	1121	799	876	1022	970
1820	792	1059	703	1228	1459	1151	748	1093	1077	1121
1830	632	1200	973	1117	619	822	971	1253	1262	988
1840	761	1416	1039	1156	921	975	852	638	1071	802
1850	956	841	1112	1159	778	1002	1185	1077	1067	950
1860	763	865	1126	1192	1008	1065	1108	819	1281	1027
1870	696	1168	641	912	1133	1086	1238	1158	1238	1004
1880	828	1061	1133	875	1140	1177	897	652	1080	934
1890	1079	1068	973	879	1077	1077	853	1079	1187	707
1900	942	1182	1053	921	1042	1418	1036	455	1089	1194
1910	938	1140	1070	815	958	1040	667	974	872	1054
1920	798	1309	977	1023	972	957	1095	1033	1053	895
1930	961	1276	990	895	1107	450	1095	1132	598	890
1940	1037	1044	1369	886	1086	1118	967	999	910	943
1950	755	1024	899	1055	720	977	743	1370	993	939
1960	845	1155	829	1261	1285	1126	634	1080	941	1224
1970	824	1127	1254	791	707	879	1211	1054	971	967
1980	954	899	1168	1096	1085	922	785	1205	1077	991
1990	1126	1230	777							

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1142			1	1	1	1	1	1	1	1
1150	1	1	1	1	1	1	1	1	1	1
1160	1	1	1	1	1	1	1	1	1	1
1170	1	1	1	1	1	1	1	1	1	1
1180	1	1	1	1	1	1	1	1	1	1
1190	1	1	1	1	1	1	1	1	1	1
1200	1	1	1	1	1	1	1	1	1	1
1210	1	1	1	1	1	1	1	1	1	1
1220	1	1	1	1	1	1	1	1	1	1
1230	1	1	1	1	1	1	1	1	1	1
1240	1	1	1	1	1	1	1	1	1	1
1250	1	1	1	1	1	1	1	2	2	2
1260	2	2	3	3	3	3	3	3	3	3
1270	3	3	3	3	3	3	3	3	3	3
1280	3	3	3	3	3	3	3	3	3	3
1290	3	3	3	3	3	3	3	3	3	3
1300	3	3	3	3	3	3	3	3	3	3
1310	3	4	4	4	4	4	4	4	4	4
1320	4	4	4	4	4	4	4	4	4	4
1330	4	4	4	4	4	4	4	4	4	4
1340	4	4	4	4	4	4	4	4	5	6
1350	6	6	6	6	6	6	6	6	6	6
1360	6	6	6	6	7	7	7	7	7	7
1370	7	7	7	7	7	7	7	7	7	7
1380	7	8	8	8	8	9	9	9	9	9
1390	10	11	11	11	11	11	12	12	12	12
1400	12	13	13	13	13	13	13	13	13	13
1410	13	14	13	13	13	14	15	15	15	15
1420	15	15	15	15	15	16	16	16	17	18
1430	18	17	17	17	18	19	20	20	20	20
1440	20	20	21	21	21	21	21	21	21	21
1450	21	22	22	22	22	22	22	22	22	22
1460	22	22	25	25	25	26	28	28	28	28
1470	28	28	28	28	28	28	28	28	28	28
1480	28	28	28	29	29	30	30	30	30	30
1490	30	30	30	30	30	30	30	30	30	30
1500	30	31	31	32	32	32	32	32	32	33
1510	34	34	34	34	34	34	34	34	35	35
1520	35	35	35	35	35	35	35	35	35	35
1530	35	35	35	35	35	35	35	35	35	36
1540	36	36	37	37	37	37	37	37	37	37
1550	37	37	37	37	37	37	37	37	37	37
1560	37	37	37	37	37	37	36	36	36	36
1570	36	36	36	36	36	36	36	36	36	36
1580	36	36	36	36	36	36	36	35	35	35
1590	35	36	36	36	36	36	36	36	36	36
1600	36	36	36	37	37	37	37	37	37	37
1610	36	38	38	38	38	38	38	38	38	38
1620	38	38	38	38	38	38	38	38	38	38
1630	38	39	39	40	40	41	41	41	41	41
1640	41	40	40	40	40	40	40	40	40	40
1650	40	40	41	41	41	41	42	42	43	43
1660	43	43	44	44	44	44	44	44	44	44
1670	44	44	44	44	44	44	44	44	44	44
1680	45	47	47	47	47	47	47	47	47	47
1690	47	47	47	47	47	47	47	47	47	47
1700	47	48	48	48	48	48	48	48	48	48
1710	48	46	46	46	46	46	46	46	46	47
1720	47	48	48	47	47	47	47	47	47	47
1730	47	47	47	47	47	47	47	48	48	48
1740	49	47	48	48	48	48	48	49	49	50
1750	50	49	49	49	49	49	49	49	49	50
1760	50	49	49	49	49	48	49	50	50	50
1770	50	49	49	49	49	49	49	49	49	49
1780	49	49	49	49	49	49	49	49	49	49
1790	49	49	49	49	48	47	47	47	47	47
1800	48	48	48	48	48	48	48	48	48	47
1810	47	47	47	47	47	47	47	47	47	47
1820	47	47	48	48	48	48	48	48	48	48
1830	48	47	47	47	46	46	46	46	46	46
1840	46	46	45	45	45	44	44	42	42	42
1850	42	42	42	42	42	42	42	42	42	42
1860	42	42	42	42	42	42	42	42	42	42
1870	42	42	42	42	42	42	42	42	42	42
1880	42	42	42	42	42	42	42	42	42	42
1890	42	42	42	42	42	42	42	41	41	41
1900	41	41	41	40	40	40	40	38	37	37
1910	37	36	36	36	36	36	36	36	36	36
1920	36	36	36	36	36	35	35	35	35	35
1930	35	35	35	35	34	33	33	32	32	32
1940	32	32	32	32	32	32	31	31	31	31
1950	29	26	26	26	26	26	26	26	26	26
1960	25	25	25	25	25	25	25	25	25	25
1970	25	25	25	25	25	24	24	14	14	14
1980	14	13	13	12	12	12	12	11	11	11
1990	11	11	9							

Site and collection information (WBF)

Site name: Werberforce **Site abbr.:** WBF
Country: New Zealand **State or Province:** South Island
Latitude: 43°04'S **Longitude:** 171°16.5'E **Altitude:** 780m
Species collected: *Libocedrus bidwillii*
Date of collection: 24 January 1994
Collector(s): L. Xiong, J. G. Palmer, B. E. Smith
No. of trees/cores sampled: 16/38 **No. of discs:** 0

Site description:

In the glacially-scoured valley of the Unknown River, a tributary of the large Wilberforce Valley just to the east of the main divide in the Southern Alps. Access was by helicopter.*Libocedrus bidwillii* occurs extensively in association mainly with *Phyllocladus alpinus* and *Podocarpus hallii*. There are also some other less abundant species like *Dacrydium biforme, P. hallii, Griselinia littoralis*, and *Hoheria glabrata*. The mos common subcanopy species is *Myrsine divaricata* and the dominate of the understory is the 0.5 - 1.0 m tall fern *Polystichum vestitum*. *Libocedrus bidwillii* in this site has a size-class distribution truncated in the smaller size-classes and most of the stem is in the 5-34 cm dbh size range. Two subsites (A & B) have been cored at different altitude. Please refer to Veblen & Stewart (1981) for more information.

Summary of chronology statistics:

Chronology 1674 to 1992 (319 years) 15 trees 31 radii

Chronology type	STNDRD	RESID (AR 1)	ARSTAN
Mean	1.0000	1.0000	.9998
Median	.9895	1.0008	.9961
Mean sensitivity	.1406	.1742	.1506
Standard deviation	.2336	.1627	.1729
Skewness	.9009	.6044	.2998
Kurtosis	3.8430	5.8907	3.8090
Autocorrelation order 1	.6667	-.0414	.3443
Partial autocorr order 2	.0616	-.0032	.0258
Partial autocorr order 3	.0912	.0382	.0357
Variance due to autoregression	29.5%		9.7%
Error variance	.022317		.008275
Ratio of error variance of chronologies (ARSTAN/STNDRD)			.3708

Common interval 1861 to 1992 (132 years) 14 trees 25 radii

	Detrended series	Residuals (white noise)
Mean correlations:		
Among all radii	.360	.416
Between trees (Y variance)	.348	.406
Within trees	.586	.598
Signal-to-noise ratio	7.475	9.586
Agreement with population chron	.882	.906
Variance in first eigenvector	39.70%	44.30%
Chron common interval mean	1.005	1.018
Chron common interval std dev	.194	.160

Chronology listings

Residual Chronology of WBF:

	Tree-Ring Indices										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1679										967										1
1680	1048	932	1017	1131	1258	749	1046	456	800	1501	1	1	1	2	2	2	3	3	3	3
1690	429	1049	552	1279	1283	1058	1055	1184	915	693	3	3	3	3	3	3	3	3	3	3
1700	764	998	893	891	1032	824	988	579	905	640	3	3	3	3	3	3	3	3	3	3
1710	829	925	937	865	1175	992	754	574	953	1061	3	3	3	3	3	3	3	3	3	3
1720	1098	964	944	960	1010	881	948	1058	1286	995	3	3	4	4	5	5	5	5	5	5
1730	1004	914	1012	1096	872	952	933	932	1091	762	5	5	5	5	6	6	6	6	6	6
1740	811	949	663	980	1028	1050	1191	1268	1075	933	6	6	6	6	6	6	6	6	6	7
1750	1049	923	1000	970	1093	1149	1103	909	987	1079	7	7	7	7	7	7	7	8	8	8
1760	611	1087	877	876	883	868	1010	990	1217	942	8	8	8	9	10	10	10	10	10	10
1770	1202	1080	1012	946	1043	913	1168	1019	1122	1287	10	11	11	11	11	11	11	11	11	11
1780	963	844	1094	811	1011	1276	1085	997	1217	795	11	11	11	11	11	11	11	11	11	11
1790	836	960	841	952	1006	990	1395	832	857	1307	11	11	12	12	12	13	13	13	13	13
1800	1042	929	1012	953	947	1001	1047	1099	924	1006	13	13	13	13	13	13	13	13	13	13
1810	1171	1047	1231	808	1084	1058	941	1024	922	872	13	13	13	13	13	13	13	14	14	14
1820	1016	1125	946	1100	1106	995	909	1209	1125	998	14	14	15	15	15	16	18	19	19	19
1830	914	1067	872	770	916	1005	1064	1131	1079	1011	19	19	20	20	20	20	20	20	20	20
1840	845	1303	890	962	860	1415	916	823	1001	797	20	21	21	21	21	21	21	21	21	21
1850	1164	1145	1020	1076	837	1113	946	961	1002	887	21	22	22	22	22	23	23	24	24	24
1860	1067	1213	943	1078	1056	896	1235	922	1078	1067	24	25	26	26	26	26	26	26	26	26
1870	932	984	781	1125	1039	1056	802	1155	880	1191	26	26	26	26	26	26	26	26	26	26
1880	986	1015	938	929	1032	884	999	976	1007	1002	26	26	26	26	26	26	26	26	26	26
1890	1035	1044	1208	1072	909	930	2042	1022	927	1101	26	26	26	26	26	26	26	26	26	26
1900	1169	828	1113	1136	768	783	950	871	977	928	26	26	27	27	27	27	27	27	27	27
1910	891	1099	1033	1081	826	981	729	1174	949	932	27	27	27	27	27	27	27	27	27	27
1920	1002	1191	1020	837	937	1043	989	1021	1201	943	27	27	27	27	27	27	27	27	27	27
1930	890	1235	1158	1271	966	575	976	961	692	1030	27	27	27	27	27	27	27	27	27	27
1940	1302	1024	930	1098	1224	1024	1082	1096	1093	1021	27	28	29	29	29	29	29	29	29	29
1950	1110	825	1111	1149	1019	874	797	963	1211	1220	29	29	29	29	29	29	29	29	29	29
1960	1139	889	932	1169	1088	1172	995	1128	864	1273	29	29	29	29	29	29	29	29	29	29
1970	934	880	1078	825	920	1001	1001	1032	880	1084	29	29	29	29	29	29	29	29	29	29
1980	1171	974	1121	949	1008	913	819	1343	913	1047	29	29	29	29	29	29	29	29	29	29
1990	901	1017	1087								29	29	29							

Appendix Three
Recorded Climate Data

a) Recorded average February-March temperature (°C)

1850				13.8	16.9	15.5	15.8	15.4	15.8	14.5
1860	14.4	15.4	15.5	15.0	15.2	16.7	15.4	16.3	14.9	15.5
1870	15.5	15.5	16.1	16.3	15.9	15.8	16.4	15.8	14.7	15.0
1880	16.6	16.6	15.6	16.8	14.2	15.6	16.3	17.2	14.9	15.9
1890	16.2	15.6	16.1	14.8	16.0	15.7	15.3	15.6	14.0	15.2
1900	15.5	14.4	15.6	15.0	15.6	15.7	13.9	16.8	15.7	16.3
1910	16.8	16.1	13.8	15.5	15.9	14.4	17.8	16.0	16.7	15.7
1920	15.9	15.3	15.4	14.4	17.0	15.0	14.5	16.1	17.4	16.0
1930	15.4	14.5	15.5	16.4	15.5	17.5	14.9	14.7	18.2	15.8
1940	14.6	15.8	15.3	15.4	15.9	15.6	16.1	15.6	16.4	16.2
1950	15.2	16.1	16.0	15.5	17.3	17.1	16.2	17.6	17.3	16.5
1960	15.8	15.8	16.4	16.4	16.2	15.7	17.6	16.2	17.4	15.9
1970	16.8	17.5	16.6	17.0	16.7	17.5	15.2	16.4	16.8	16.6
1980	15.8	17.4	16.3	15.8	16.8	16.5	16.7	15.8	15.7	16.1
1990	17.6	15.8								

b) Recorded total March-April precipitation (mm)

1880									212	91
1890	275	193	224	295	126	155	350	277	168	186
1900	159	177	373	181	427	135	199	311	341	291
1910	206	255	330	148	245	253	265	205	321	132
1920	294	115	237	302	369	125	142	240	284	317
1930	154	202	238	185	146	390	235	211	377	130
1940	108	256	189	121	326	217	345	244	231	242
1950	143	178	105	204	374	226	369	271	110	365
1960	154	217	476	91	138	232	229	230	380	143
1970	272	224	346	245	259	276	220	146	291	323
1980	228	327	229	243	219	213	190	339	262	163
1990	347	202								

Appendix Four
Reconstructed February-March Average Temperature (°C) and March-April Total Precipitation (mm)

GRAT: temperature reconstructed from Group A.
GRAP: precipitation reconstructed from Group A.
THRT: temperature reconstructed from three longest chronologies.
THRP: precipitation reconstructed from three longest chronologies.
90%L: lower 90% confidence interval.
90%U: upper 90% confidence interval.

Year	GRAT 90%L	GRAT	GRAT 90%U	GRAP 90%L	GRAP	GRAP 90%U	THRT 90%L	THRT	THRT 90%U	THRP 90%L	THRP	THRP 90%U
1458	.	.	.	.	.	.	15.2	15.5	15.7	195.1	215.7	236.1
1459	.	.	.	.	.	.	15.7	16.1	16.4	192.3	237.9	281.5
1460	.	.	.	.	.	.	16.0	16.4	16.7	223.3	257.6	289.8
1461	.	.	.	.	.	.	15.1	15.5	15.8	198.4	232.7	254.1
1462	.	.	.	.	.	.	15.4	15.6	15.8	209.9	227.4	245.4
1463	.	.	.	.	.	.	15.7	16.1	16.4	223.0	274.8	322.0
1464	.	.	.	.	.	.	15.3	15.6	15.9	185.1	213.6	238.9
1465	.	.	.	.	.	.	15.7	15.9	16.1	224.4	247.6	277.9
1466	.	.	.	.	.	.	16.0	16.2	16.5	194.8	232.5	267.0
1467	.	.	.	.	.	.	15.8	16.1	16.3	190.8	215.9	240.5
1468	.	.	.	.	.	.	15.9	16.4	17.0	235.9	287.4	336.1
1469	.	.	.	.	.	.	15.5	15.9	16.1	204.4	248.4	276.0
1470	.	.	.	.	.	.	15.7	16.1	16.4	205.6	247.0	295.4
1471	.	.	.	.	.	.	15.8	16.0	16.3	233.2	254.2	271.4
1472	.	.	.	.	.	.	15.9	16.1	16.3	257.4	276.5	295.0
1473	.	.	.	.	.	.	15.8	16.0	16.1	252.5	266.6	283.7
1474	.	.	.	.	.	.	15.9	16.1	16.4	259.5	286.8	314.3
1475	.	.	.	.	.	.	15.6	15.8	16.0	232.5	259.1	274.8
1476	.	.	.	.	.	.	15.9	16.0	16.2	263.7	279.9	295.5
1477	.	.	.	.	.	.	15.6	15.8	16.1	249.1	277.4	303.9
1478	.	.	.	.	.	.	15.8	15.9	16.2	272.5	296.3	321.2
1479	.	.	.	.	.	.	15.5	15.7	15.9	218.8	249.9	277.2
1480	.	.	.	.	.	.	15.3	15.5	15.7	221.6	242.8	263.8
1481	.	.	.	.	.	.	15.5	15.7	15.8	207.2	223.6	242.2
1482	.	.	.	.	.	.	15.9	16.3	16.6	208.0	255.4	294.4
1483	.	.	.	.	.	.	15.4	15.7	16.1	127.4	159.0	178.9
1484	.	.	.	.	.	.	15.6	15.9	16.2	199.4	227.0	251.1
1485	.	.	.	.	.	.	15.6	15.8	16.0	174.5	195.7	219.7
1486	.	.	.	.	.	.	15.4	15.6	15.9	162.6	185.7	217.6
1487	.	.	.	.	.	.	16.1	16.4	16.7	231.9	263.5	291.7
1488	.	.	.	.	.	.	15.9	16.1	16.4	226.0	262.8	284.4
1489	.	.	.	.	.	.	14.9	15.2	15.4	157.1	185.5	222.2
1490	.	.	.	.	.	.	15.5	15.6	15.9	210.8	232.0	263.3
1491	.	.	.	.	.	.	15.3	15.6	15.9	163.6	188.0	223.2
1492	.	.	.	.	.	.	15.4	15.8	16.2	186.4	222.0	260.9
1493	.	.	.	.	.	.	15.5	15.9	16.3	138.6	177.9	224.2
1494	.	.	.	.	.	.	16.2	16.6	16.9	256.7	287.5	311.9
1495	.	.	.	.	.	.	15.3	15.6	15.8	170.8	195.5	220.8
1496	.	.	.	.	.	.	15.8	16.1	16.4	264.4	298.3	327.3
1497	.	.	.	.	.	.	15.4	15.7	16.0	218.7	255.2	282.5
1498	.	.	.	.	.	.	15.7	16.0	16.2	244.0	274.8	301.4
1499	.	.	.	.	.	.	15.8	16.0	16.3	222.7	246.8	267.5
1500	.	.	.	.	.	.	15.7	15.8	16.0	236.8	252.8	264.4
1501	.	.	.	.	.	.	15.2	15.4	15.7	171.5	191.5	216.9
1502	.	.	.	.	.	.	15.9	16.1	16.2	213.2	234.1	256.1
1503	.	.	.	.	.	.	16.0	16.2	16.3	219.2	235.5	250.1
1504	.	.	.	.	.	.	15.5	15.7	15.9	187.8	211.3	238.8
1505	.	.	.	.	.	.	15.3	15.6	15.9	161.1	196.3	227.8
1506	.	.	.	.	.	.	15.9	16.1	16.4	183.3	213.5	246.3
1507	.	.	.	.	.	.	15.5	15.9	16.2	196.0	230.4	266.5
1508	.	.	.	.	.	.	15.5	15.8	16.1	261.3	291.9	317.5
1509	.	.	.	.	.	.	15.8	15.9	16.2	258.7	279.5	302.3
1510	.	.	.	.	.	.	15.5	15.8	16.1	246.5	275.3	307.5
1511	.	.	.	.	.	.	15.4	15.6	15.9	226.2	260.4	295.9
1512	.	.	.	.	.	.	15.9	16.2	16.6	287.1	315.8	345.3
1513	.	.	.	.	.	.	15.3	15.8	16.2	203.6	241.9	286.1
1514	.	.	.	.	.	.	15.9	16.1	16.4	235.7	260.1	278.0

Year	GRAT 90%L	GRAT	GRAT 90%U	GRAP 90%L	GRAP	GRAP 90%U	THRT 90%L	THRT	THRT 90%U	THRP 90%L	THRP	THRP 90%U
1515	.	.	.	.	.	.	15.3	15.8	16.2	193.1	239.4	279.3
1516	.	.	.	.	.	.	15.4	15.7	15.9	238.7	253.8	275.3
1517	.	.	.	.	.	.	15.7	15.9	16.2	194.8	225.8	257.4
1518	.	.	.	.	.	.	15.6	15.9	16.1	191.7	211.7	225.5
1519	.	.	.	.	.	.	15.7	15.8	16.0	214.2	231.5	250.5
1520	.	.	.	.	.	.	16.0	16.1	16.2	252.5	266.5	277.0
1521	.	.	.	.	.	.	15.7	15.8	15.8	213.0	232.4	244.0
1522	.	.	.	.	.	.	15.2	15.3	15.5	189.7	216.8	248.2
1523	.	.	.	.	.	.	15.6	15.8	16.1	219.6	240.4	258.2
1524	.	.	.	.	.	.	15.7	16.0	16.2	196.4	220.9	246.5
1525	.	.	.	.	.	.	16.0	16.2	16.4	228.3	244.8	264.8
1526	.	.	.	.	.	.	15.6	15.8	16.0	190.3	210.8	235.9
1527	.	.	.	.	.	.	15.8	15.9	16.1	223.8	239.1	258.0
1528	.	.	.	.	.	.	16.0	16.1	16.2	228.2	244.1	260.2
1529	.	.	.	.	.	.	16.0	16.1	16.3	232.3	249.3	262.9
1530	.	.	.	.	.	.	15.7	15.9	16.1	227.8	242.3	254.9
1531	.	.	.	.	.	.	15.8	15.9	16.0	233.5	243.2	252.5
1532	.	.	.	.	.	.	15.7	16.0	16.3	198.9	234.5	269.4
1533	.	.	.	.	.	.	15.7	16.1	16.3	185.8	213.3	244.5
1534	.	.	.	.	.	.	15.7	16.1	16.4	212.6	247.9	287.4
1535	.	.	.	.	.	.	15.7	16.0	16.2	222.8	244.2	268.2
1536	.	.	.	.	.	.	15.5	15.6	15.8	200.0	210.2	230.5
1537	.	.	.	.	.	.	15.4	15.5	15.8	187.3	202.2	225.1
1538	.	.	.	.	.	.	15.9	16.2	16.3	225.7	247.4	271.5
1539	.	.	.	.	.	.	15.8	16.1	16.3	228.3	255.8	275.9
1540	.	.	.	.	.	.	15.5	15.8	16.0	196.8	230.9	264.7
1541	.	.	.	.	.	.	15.6	15.9	16.1	217.5	245.2	275.6
1542	.	.	.	.	.	.	16.0	16.3	16.6	255.0	283.9	311.8
1543	.	.	.	.	.	.	15.9	16.2	16.4	227.3	256.9	281.9
1544	.	.	.	.	.	.	15.7	16.0	16.3	256.4	293.7	324.1
1545	.	.	.	.	.	.	15.4	15.7	15.9	225.0	250.3	270.1
1546	.	.	.	.	.	.	15.8	15.9	16.1	249.1	262.0	276.3
1547	.	.	.	.	.	.	15.4	15.7	16.0	176.9	211.0	243.4
1548	.	.	.	.	.	.	15.7	16.0	16.3	184.9	213.2	255.3
1549	.	.	.	.	.	.	15.2	15.6	16.0	152.7	185.8	228.2
1550	.	.	.	.	.	.	15.5	15.7	15.9	184.7	203.1	233.4
1551	.	.	.	.	.	.	15.2	15.4	15.7	152.6	172.6	203.1
1552	.	.	.	.	.	.	16.6	17.1	17.6	271.2	312.4	350.8
1553	.	.	.	.	.	.	15.7	16.0	16.4	150.9	217.5	254.8
1554	.	.	.	.	.	.	15.1	15.6	16.1	183.5	225.2	265.4
1555	.	.	.	.	.	.	15.4	15.7	16.0	220.9	255.2	289.8
1556	.	.	.	.	.	.	16.0	16.1	16.3	256.2	268.6	278.7
1557	.	.	.	.	.	.	15.7	15.9	16.0	213.1	228.1	242.2
1558	.	.	.	.	.	.	16.0	16.1	16.2	245.2	257.0	264.0
1559	.	.	.	.	.	.	15.2	15.4	15.7	173.8	196.0	225.5
1560	.	.	.	.	.	.	15.5	15.9	16.2	206.8	235.4	272.1
1561	.	.	.	.	.	.	15.6	15.9	16.1	205.7	226.4	250.1
1562	.	.	.	.	.	.	15.8	15.9	16.1	199.5	215.9	237.2
1563	.	.	.	.	.	.	15.8	16.0	16.1	233.5	248.1	263.0
1564	.	.	.	.	.	.	15.8	15.9	15.9	243.1	249.6	258.6
1565	.	.	.	.	.	.	15.5	15.7	15.9	215.5	235.6	255.8
1566	.	.	.	.	.	.	16.2	16.4	16.7	260.7	286.5	308.6
1567	.	.	.	.	.	.	15.9	16.2	16.4	250.4	281.7	302.6
1568	.	.	.	.	.	.	15.6	15.9	16.1	225.1	248.4	268.0
1569	.	.	.	.	.	.	15.8	16.0	16.1	248.8	269.4	284.6
1570	.	.	.	.	.	.	15.9	16.0	16.2	238.4	251.8	263.7
1571	.	.	.	.	.	.	15.2	15.4	15.6	172.1	183.3	198.0
1572	.	.	.	.	.	.	15.8	16.0	16.1	214.8	234.7	255.8
1573	.	.	.	.	.	.	15.5	15.7	15.9	162.8	180.4	197.4
1574	.	.	.	.	.	.	15.6	15.7	15.9	194.8	208.7	227.2
1575	.	.	.	.	.	.	15.8	15.9	16.0	213.2	224.3	237.9
1576	.	.	.	.	.	.	16.1	16.4	16.5	237.0	260.3	277.5
1577	.	.	.	.	.	.	15.8	16.0	16.2	209.5	235.7	254.9
1578	.	.	.	.	.	.	15.3	15.6	15.9	200.0	218.5	239.3
1579	.	.	.	.	.	.	16.2	16.5	16.6	287.0	304.7	320.9
1580	.	.	.	.	.	.	15.7	15.9	16.1	201.9	232.0	252.0
1581	.	.	.	.	.	.	15.8	16.0	16.2	229.3	249.5	268.8
1582	.	.	.	.	.	.	15.6	15.8	16.1	208.5	233.2	258.8
1583	.	.	.	.	.	.	15.4	15.6	15.8	207.1	220.5	241.4
1584	.	.	.	.	.	.	15.7	15.8	15.9	209.1	218.9	232.5
1585	.	.	.	.	.	.	15.9	16.0	16.2	240.0	259.1	275.9
1586	.	.	.	.	.	.	15.4	15.5	15.7	196.9	205.7	218.3
1587	.	.	.	.	.	.	15.4	15.6	15.8	195.9	215.1	241.8
1588	.	.	.	.	.	.	15.7	16.0	16.3	194.3	235.4	272.3
1589	.	.	.	.	.	.	15.9	16.1	16.3	211.1	236.7	260.2
1590	.	.	.	.	.	.	15.7	15.9	16.0	223.9	234.0	244.4
1591	.	.	.	.	.	.	16.0	16.0	16.1	240.4	246.8	252.3
1592	.	.	.	.	.	.	15.6	15.8	16.1	213.7	240.3	267.2
1593	.	.	.	.	.	.	15.1	15.3	15.5	184.4	205.1	235.6
1594	.	.	.	.	.	.	15.8	16.1	16.4	229.8	254.6	281.9
1595	.	.	.	.	.	.	15.5	15.7	15.9	170.0	192.7	212.5

Year	GRAT 90%L	GRAT	GRAT 90%U	GRAP 90%L	GRAP	GRAP 90%U	THRT 90%L	THRT	THRT 90%U	THRP 90%L	THRP	THRP 90%U
1596	.	.	.	.	.	.	15.8	16.0	16.3	223.1	236.4	267.4
1597	.	.	.	.	.	.	16.2	16.3	16.5	244.9	262.6	278.6
1598	.	.	.	.	.	.	15.9	16.1	16.5	237.8	270.1	296.1
1599	.	.	.	.	.	.	15.4	15.7	15.9	201.8	228.2	253.7
1600	.	.	.	.	.	.	15.6	15.8	16.0	208.2	224.9	247.3
1601	.	.	.	.	.	.	15.8	15.9	16.0	214.0	223.1	232.7
1602	.	.	.	.	.	.	16.4	16.7	16.9	282.7	315.4	340.3
1603	.	.	.	.	.	.	15.8	16.1	16.3	232.8	268.9	291.7
1604	.	.	.	.	.	.	15.2	15.6	15.9	183.2	220.0	248.4
1605	.	.	.	.	.	.	15.4	15.8	16.1	176.6	200.9	241.8
1606	.	.	.	.	.	.	15.7	15.9	16.2	180.5	201.2	239.9
1607	.	.	.	.	.	.	16.0	16.1	16.4	202.5	226.9	255.2
1608	.	.	.	.	.	.	15.8	15.9	16.1	208.8	222.4	238.4
1609	.	.	.	.	.	.	15.8	16.0	16.1	238.5	254.6	269.5
1610	.	.	.	.	.	.	15.2	15.5	15.6	179.6	205.9	231.8
1611	.	.	.	.	.	.	16.5	16.8	17.1	317.5	336.2	361.3
1612	.	.	.	.	.	.	15.8	16.1	16.4	178.0	232.4	264.4
1613	.	.	.	.	.	.	15.3	15.7	16.2	215.1	253.9	285.9
1614	.	.	.	.	.	.	15.8	16.1	16.4	272.1	301.0	328.1
1615	.	.	.	.	.	.	15.6	15.7	15.9	230.2	247.2	266.8
1616	.	.	.	.	.	.	15.9	16.0	16.1	254.8	265.9	276.5
1617	.	.	.	.	.	.	15.5	15.5	15.6	193.4	203.3	212.3
1618	.	.	.	.	.	.	15.9	16.0	16.0	238.6	248.9	257.3
1619	.	.	.	.	.	.	15.4	15.5	15.7	184.0	196.1	210.8
1620	.	.	.	.	.	.	15.7	15.9	16.0	215.9	230.8	248.7
1621	.	.	.	.	.	.	15.7	15.8	16.0	198.6	212.0	226.4
1622	.	.	.	.	.	.	16.8	17.1	17.4	304.7	347.2	377.7
1623	.	.	.	.	.	.	15.5	15.9	16.2	168.3	212.3	240.9
1624	.	.	.	.	.	.	15.2	15.6	16.1	196.1	234.3	265.5
1625	.	.	.	.	.	.	16.1	16.4	16.6	253.7	286.0	309.6
1626	.	.	.	.	.	.	15.3	15.5	15.7	179.9	213.0	236.7
1627	.	.	.	.	.	.	14.7	15.1	15.5	151.1	189.0	219.8
1628	.	.	.	.	.	.	15.9	16.2	16.3	210.0	237.5	261.3
1629	.	.	.	.	.	.	15.2	15.5	15.8	155.7	174.9	203.8
1630	.	.	.	.	.	.	15.5	15.8	15.9	208.9	235.3	261.3
1631	.	.	.	.	.	.	15.4	15.7	15.9	151.3	175.0	196.2
1632	.	.	.	.	.	.	15.5	15.7	16.0	171.1	189.9	218.4
1633	.	.	.	.	.	.	16.3	16.6	16.8	254.3	281.0	307.9
1634	.	.	.	.	.	.	15.8	16.0	16.3	194.2	224.1	246.2
1635	.	.	.	.	.	.	15.4	15.6	15.8	213.8	237.0	259.7
1636	.	.	.	.	.	.	15.1	15.3	15.5	172.7	186.8	215.4
1637	.	.	.	.	.	.	16.3	16.5	16.7	285.7	301.7	316.7
1638	.	.	.	.	.	.	15.5	15.8	16.0	201.0	233.0	260.4
1639	.	.	.	.	.	.	15.6	15.8	16.0	261.7	277.9	297.9
1640	.	.	.	.	.	.	15.3	15.4	15.6	177.7	202.9	227.4
1641	.	.	.	.	.	.	14.7	15.0	15.4	127.3	158.6	220.2
1642	.	.	.	.	.	.	15.1	15.5	16.0	144.7	188.1	240.8
1643	.	.	.	.	.	.	15.7	16.1	16.5	166.1	205.5	247.5
1644	.	.	.	.	.	.	15.7	15.9	16.2	190.5	217.0	240.9
1645	.	.	.	.	.	.	15.5	15.7	15.8	191.0	206.8	227.0
1646	.	.	.	.	.	.	15.8	15.9	16.0	225.7	233.4	240.9
1647	.	.	.	.	.	.	15.1	15.3	15.5	154.1	174.0	204.2
1648	.	.	.	.	.	.	15.5	15.8	16.0	228.2	246.2	266.9
1649	.	.	.	.	.	.	15.6	15.9	16.2	204.2	220.9	246.4
1650	.	.	.	.	.	.	15.8	16.0	16.2	221.3	241.0	262.4
1651	.	.	.	.	.	.	15.9	16.1	16.2	230.7	242.3	254.7
1652	.	.	.	.	.	.	16.7	17.2	17.5	330.7	376.3	410.7
1653	.	.	.	.	.	.	15.1	15.4	15.8	187.1	232.4	279.1
1654	.	.	.	.	.	.	15.3	15.6	15.9	254.5	297.3	339.4
1655	.	.	.	.	.	.	15.5	15.8	16.0	223.5	242.2	262.0
1656	.	.	.	.	.	.	15.5	15.6	15.7	217.7	226.9	240.4
1657	.	.	.	.	.	.	15.7	16.0	16.3	241.0	271.0	305.9
1658	.	.	.	.	.	.	15.4	15.7	16.0	220.5	248.0	271.9
1659	.	.	.	.	.	.	15.5	15.8	16.0	210.2	235.1	262.0
1660	.	.	.	.	.	.	15.8	15.9	16.0	217.0	231.0	243.0
1661	.	.	.	.	.	.	15.6	15.7	15.7	216.3	228.2	238.5
1662	.	.	.	.	.	.	16.3	16.6	16.8	280.6	313.3	336.1
1663	.	.	.	.	.	.	15.5	15.8	16.1	197.6	235.7	263.2
1664	.	.	.	.	.	.	15.8	16.1	16.4	253.6	286.8	313.7
1665	.	.	.	.	.	.	15.9	16.0	16.2	236.4	254.8	273.2
1666	.	.	.	.	.	.	15.5	15.8	16.1	230.1	261.6	290.3
1667	.	.	.	.	.	.	15.5	15.6	15.9	240.7	263.9	291.1
1668	.	.	.	.	.	.	15.2	15.5	15.8	207.9	225.8	252.7
1669	.	.	.	.	.	.	15.2	15.4	15.7	170.3	195.2	228.9
1670	.	.	.	.	.	.	16.2	16.3	16.5	237.7	256.4	277.5
1671	.	.	.	.	.	.	14.8	15.1	15.4	110.8	140.2	171.0
1672	.	.	.	.	.	.	15.4	15.7	16.0	195.1	227.8	253.7
1673	.	.	.	.	.	.	16.5	16.8	17.1	243.3	283.0	320.5
1674	.	.	.	.	.	.	15.5	15.7	16.0	192.1	218.3	246.7
1675	.	.	.	.	.	.	15.4	15.7	15.9	228.7	253.4	273.2
1676	.	.	.	.	.	.	15.6	15.7	15.8	215.0	225.2	237.9

Year	GRAT 90%L	GRAT	GRAT 90%U	GRAP 90%L	GRAP	GRAP 90%U	THRT 90%L	THRT	THRT 90%U	THRP 90%L	THRP	THRP 90%U
1677	.	.	.	.	.	.	15.4	15.6	15.8	181.6	197.8	227.4
1678	.	.	.	.	.	.	16.6	16.9	17.2	299.1	332.0	362.9
1679	.	.	.	.	.	.	15.1	15.4	15.7	157.7	179.4	205.1
1680	.	.	.	.	.	.	15.5	15.8	16.1	245.3	275.2	308.4
1681	.	.	.	.	.	.	15.8	15.9	16.1	204.4	226.0	242.3
1682	.	.	.	.	.	.	16.7	17.0	17.2	279.1	333.2	366.4
1683	.	.	.	.	.	.	15.2	15.6	16.0	172.5	199.6	235.6
1684	.	.	.	.	.	.	15.4	15.8	16.2	235.0	272.5	313.5
1685	.	.	.	.	.	.	15.6	15.8	15.9	219.9	236.6	251.9
1686	.	.	.	.	.	.	15.9	16.0	16.1	242.0	256.4	270.0
1687	.	.	.	.	.	.	15.4	15.7	16.0	210.2	252.9	293.0
1688	.	.	.	.	.	.	15.2	15.5	15.7	207.0	239.3	269.7
1689	.	.	.	.	.	.	14.8	15.2	15.5	155.3	184.3	220.9
1690	.	.	.	.	.	.	15.4	15.6	15.9	189.2	210.1	248.4
1691	.	.	.	.	.	.	15.8	16.2	16.5	228.2	253.6	282.4
1692	.	.	.	.	.	.	15.4	15.8	16.1	172.2	206.0	239.9
1693	.	.	.	.	.	.	15.3	15.6	15.7	174.9	189.4	209.7
1694	.	.	.	.	.	.	16.2	16.2	16.3	238.7	257.0	273.1
1695	.	.	.	.	.	.	15.8	15.9	16.0	203.6	215.5	224.1
1696	.	.	.	.	.	.	15.9	16.0	16.2	237.5	253.2	267.7
1697	.	.	.	.	.	.	15.7	15.8	15.8	223.1	232.6	238.3
1698	.	.	.	.	.	.	15.5	15.6	15.7	198.7	212.2	232.0
1699	.	.	.	.	.	.	15.8	16.0	16.1	235.5	245.6	255.8
1700	.	.	.	.	.	.	15.5	15.7	15.8	183.5	197.0	210.8
1701	.	.	.	.	.	.	15.5	15.6	15.8	202.7	211.8	227.8
1702	.	.	.	.	.	.	15.8	15.9	16.1	226.2	237.6	252.7
1703	.	.	.	.	.	.	14.8	15.1	15.3	136.3	167.6	200.7
1704	.	.	.	.	.	.	15.9	16.2	16.5	259.5	279.9	299.1
1705	.	.	.	.	.	.	16.0	16.4	16.8	239.4	269.7	299.8
1706	.	.	.	.	.	.	15.0	15.2	15.4	160.7	189.5	221.6
1707	.	.	.	.	.	.	15.8	16.1	16.4	243.9	280.1	315.4
1708	.	.	.	.	.	.	16.2	16.4	16.7	203.2	239.8	272.2
1709	.	.	.	.	.	.	15.8	16.1	16.4	224.9	248.8	274.7
1710	.	.	.	.	.	.	15.6	15.8	16.1	215.3	234.9	256.9
1711	.	.	.	.	.	.	15.3	15.4	15.6	187.9	206.1	228.0
1712	.	.	.	.	.	.	15.3	15.5	15.7	183.3	201.2	228.5
1713	.	.	.	.	.	.	16.1	16.4	16.6	242.5	261.6	285.7
1714	.	.	.	.	.	.	15.2	15.4	15.6	148.2	175.5	198.3
1715	.	.	.	.	.	.	15.5	15.7	15.9	227.6	246.3	266.4
1716	.	.	.	.	.	.	15.6	15.9	16.1	197.1	220.9	246.3
1717	.	.	.	.	.	.	16.3	16.7	16.9	246.3	292.9	330.5
1718	.	.	.	.	.	.	15.7	16.0	16.3	188.7	209.1	234.7
1719	.	.	.	.	.	.	15.4	15.9	16.3	203.1	242.2	276.4
1720	16.6	17.0	17.4	176.3	233.2	279.2	15.7	15.8	15.9	205.3	221.3	236.8
1721	16.1	16.5	16.8	199.4	236.2	262.3	15.6	15.8	16.0	198.6	214.3	234.2
1722	16.1	16.4	16.6	239.7	271.7	301.6	16.2	16.3	16.5	239.3	262.5	284.3
1723	15.7	16.1	16.6	230.0	272.9	308.9	15.7	15.9	16.1	214.5	225.1	239.6
1724	15.4	16.0	16.3	194.6	229.2	251.8	15.7	15.9	16.2	249.9	277.3	305.6
1725	15.1	15.5	15.9	186.4	235.4	273.7	15.3	15.5	15.7	209.0	234.0	255.3
1726	15.4	15.7	16.1	247.3	292.6	329.9	15.7	15.9	16.1	253.8	264.1	278.8
1727	15.1	15.5	16.0	168.8	218.4	254.7	15.3	15.6	15.7	188.5	202.8	220.6
1728	15.7	16.3	16.7	114.3	167.4	197.5	14.9	15.2	15.4	157.5	179.8	213.0
1729	16.8	17.2	17.7	221.0	268.4	317.0	16.2	16.4	16.7	251.2	276.7	303.8
1730	15.1	15.4	16.1	119.0	179.6	216.7	15.1	15.4	15.6	139.4	163.1	197.6
1731	16.1	16.6	17.4	232.9	286.7	338.6	16.9	17.2	17.6	325.9	363.4	398.0
1732	15.0	15.6	16.0	180.6	241.3	282.9	15.7	16.1	16.5	180.8	231.4	261.5
1733	15.5	16.0	16.4	231.0	280.0	322.1	15.2	15.6	16.1	200.3	243.8	289.0
1734	15.5	15.8	16.2	166.0	199.6	246.8	15.9	16.0	16.2	240.4	252.9	264.1
1735	15.4	15.7	15.9	167.1	201.9	238.3	15.5	15.7	15.8	186.2	207.8	230.0
1736	15.3	15.8	16.1	155.2	225.1	280.2	15.2	15.3	15.5	181.3	197.4	226.8
1737	16.3	16.6	16.9	218.8	245.7	269.3	16.0	16.4	16.7	228.2	267.3	304.5
1738	15.4	15.7	16.1	161.7	199.3	223.5	15.7	15.9	16.1	191.7	205.3	227.6
1739	14.5	15.1	15.5	245.3	282.0	331.0	15.4	15.7	16.0	204.1	230.2	264.1
1740	16.0	16.3	16.6	208.2	244.6	274.8	16.0	16.0	16.2	252.4	258.0	265.3
1741	16.4	16.7	17.2	244.9	276.4	331.4	16.6	17.0	17.2	294.6	332.0	364.3
1742	14.9	15.4	16.0	208.3	248.7	301.9	15.3	15.6	15.9	177.7	212.3	244.5
1743	15.3	15.7	16.0	232.3	273.1	295.4	15.2	15.5	15.8	215.0	248.0	275.6
1744	15.7	16.3	16.7	158.0	219.9	272.8	16.0	16.3	16.5	248.4	269.7	290.6
1745	14.9	15.5	15.9	202.1	248.7	292.6	15.8	15.9	16.0	203.6	216.7	227.1
1746	15.6	16.2	16.6	219.9	258.2	317.8	16.1	16.3	16.5	266.7	288.4	300.3
1747	15.4	15.7	16.0	212.7	243.9	288.4	15.8	15.9	16.0	219.2	239.6	250.6
1748	15.1	15.2	15.5	187.6	218.8	242.7	15.4	15.6	15.7	201.7	218.6	233.0
1749	14.9	15.3	15.6	232.7	277.4	320.0	15.5	15.6	15.7	202.1	213.1	234.2
1750	16.2	16.5	16.8	227.1	276.6	314.9	15.9	16.0	16.2	237.5	252.3	264.6
1751	14.9	15.2	15.5	168.1	192.1	231.9	15.7	15.8	15.9	212.7	221.9	234.3
1752	16.1	16.5	17.0	263.5	295.0	350.4	16.7	17.1	17.3	320.6	355.9	376.5
1753	15.6	16.0	16.3	154.4	233.4	283.3	15.5	15.8	16.2	184.8	229.0	260.3
1754	15.2	15.7	16.3	261.4	302.8	348.0	15.3	15.7	16.0	221.7	256.7	280.4
1755	15.5	15.9	16.3	184.4	237.4	282.6	15.8	15.9	16.0	222.7	233.5	250.1
1756	15.8	16.1	16.5	141.6	183.8	235.5	16.1	16.2	16.4	255.5	272.6	288.4
1757	15.2	15.6	16.1	217.1	240.1	284.3	15.7	15.8	15.9	217.2	228.7	238.8

Year	GRAT 90%L	GRAT	GRAT 90%U	GRAP 90%L	GRAP	GRAP 90%U	THRT 90%L	THRT	THRT 90%U	THRP 90%L	THRP	THRP 90%U
1758	15.6	15.9	16.2	194.8	237.4	281.1	15.9	16.1	16.2	251.4	264.1	274.5
1759	15.4	15.8	16.2	138.8	184.9	234.4	15.6	15.7	15.8	211.8	221.8	230.8
1760	14.8	15.1	15.4	156.8	205.9	250.4	15.6	15.7	15.8	218.7	231.8	241.8
1761	14.9	15.5	15.8	131.6	205.6	270.9	15.4	15.5	15.7	178.9	191.8	211.0
1762	14.9	15.4	15.7	189.7	235.0	288.2	15.9	16.0	16.2	233.3	247.8	266.6
1763	16.1	16.3	16.6	215.9	247.6	281.4	15.5	15.7	15.9	199.3	215.2	229.9
1764	15.3	15.6	15.8	213.0	260.9	309.6	15.8	16.0	16.1	235.6	250.2	266.7
1765	15.5	16.0	16.3	274.0	306.9	355.2	16.3	16.4	16.6	247.3	271.0	289.0
1766	15.2	15.4	15.9	199.8	234.7	266.4	15.6	15.8	16.0	202.4	232.1	247.3
1767	15.9	16.5	16.8	253.5	294.9	330.2	15.8	16.3	16.7	244.1	284.4	319.6
1768	15.5	16.0	16.6	208.6	247.0	310.1	15.8	16.0	16.2	248.6	271.4	294.7
1769	15.5	16.0	16.4	169.3	214.8	251.5	15.1	15.4	15.6	169.1	198.4	229.6
1770	16.0	16.4	16.8	260.8	298.1	346.1	16.4	16.5	16.8	269.0	298.4	328.7
1771	15.7	16.2	16.6	181.0	235.1	279.4	15.5	15.7	16.0	176.6	193.2	214.7
1772	14.5	14.9	15.2	223.9	279.6	313.1	15.4	15.6	15.8	208.8	227.9	248.1
1773	15.2	15.7	16.4	180.6	233.0	292.3	15.7	15.8	15.9	194.6	211.5	224.9
1774	15.4	15.6	16.0	207.7	256.8	285.6	15.9	16.0	16.1	217.2	231.8	251.7
1775	14.6	15.1	15.4	197.8	238.7	261.7	15.6	15.7	15.8	199.7	206.0	215.9
1776	15.4	15.7	16.2	200.2	246.6	286.3	16.2	16.3	16.4	253.9	268.7	277.3
1777	15.5	15.8	16.3	184.2	226.4	265.0	15.3	15.5	15.7	145.0	172.8	194.8
1778	15.8	16.2	16.4	165.4	224.5	265.2	15.7	16.0	16.3	198.3	230.9	263.8
1779	16.1	16.4	16.9	146.0	189.7	236.2	15.7	16.0	16.3	184.2	215.4	250.3
1780	15.5	16.0	16.5	145.0	228.6	290.4	15.9	16.1	16.3	220.2	244.9	270.2
1781	15.5	15.9	16.3	227.2	257.9	299.1	16.0	16.2	16.5	253.9	277.0	303.6
1782	15.5	15.9	16.2	143.5	208.6	256.2	16.0	16.2	16.3	261.5	282.4	296.9
1783	15.1	15.5	15.8	188.2	237.1	286.4	15.6	15.7	15.9	223.2	246.9	272.5
1784	15.2	15.8	16.4	194.6	241.0	284.2	15.7	15.9	16.0	247.8	261.0	277.8
1785	15.4	15.8	16.2	206.0	237.3	272.4	15.9	16.0	16.1	215.8	230.9	246.1
1786	14.9	15.3	15.6	193.4	233.7	266.8	15.6	15.7	15.8	213.4	225.5	239.4
1787	15.9	16.2	16.6	237.8	281.0	339.9	15.8	15.9	15.9	242.4	250.9	262.5
1788	15.7	16.2	16.4	215.7	271.3	310.1	15.9	16.0	16.1	243.4	253.1	264.7
1789	15.1	15.3	15.6	198.3	240.5	264.2	15.6	15.6	15.7	208.5	215.3	225.9
1790	16.3	16.8	17.0	217.8	265.0	300.3	15.7	15.8	15.9	221.2	228.8	240.0
1791	15.2	15.6	16.0	194.4	241.8	279.9	16.1	16.1	16.3	248.4	258.6	269.0
1792	15.8	16.0	16.3	231.6	265.6	306.8	16.0	16.1	16.2	240.2	256.4	270.8
1793	15.7	16.0	16.4	198.6	238.5	297.7	15.5	15.6	15.7	212.6	224.5	239.4
1794	15.0	15.5	15.9	209.4	246.5	289.9	15.8	15.9	16.0	236.2	249.2	263.2
1795	15.2	15.6	16.0	224.5	271.0	300.8	15.5	15.7	15.8	193.8	204.9	215.7
1796	16.1	16.4	16.7	228.6	261.7	287.2	16.0	16.1	16.2	246.6	261.2	275.8
1797	15.6	16.1	16.7	144.9	208.5	250.7	15.4	15.6	15.8	173.2	189.5	205.8
1798	15.4	15.8	16.3	240.8	285.5	334.2	16.0	16.2	16.4	248.5	271.9	292.5
1799	15.4	15.8	16.2	129.1	178.7	215.5	14.9	15.2	15.4	134.6	163.6	194.3
1800	15.4	15.9	16.2	136.2	209.2	262.0	15.0	15.3	15.7	156.2	185.7	234.5
1801	15.4	16.0	16.6	142.7	206.0	268.2	15.0	15.5	15.9	119.1	166.8	214.7
1802	15.5	15.9	16.4	191.1	231.3	296.5	15.6	15.9	16.1	164.0	194.6	224.5
1803	15.9	16.3	16.8	214.5	258.4	306.5	16.4	16.7	17.0	265.5	302.7	336.8
1804	14.4	14.8	15.2	137.8	178.5	210.2	15.1	15.3	15.7	140.8	176.2	213.2
1805	15.1	15.8	16.4	172.1	232.7	279.5	14.5	14.9	15.2	146.7	187.3	242.1
1806	15.6	16.0	16.5	168.4	235.2	283.7	15.7	16.3	16.8	179.1	230.6	291.8
1807	15.6	16.0	16.4	194.3	234.3	285.0	16.0	16.2	16.5	156.3	195.9	225.4
1808	15.9	16.2	16.6	177.5	225.2	302.9	15.8	16.1	16.4	233.7	260.7	289.7
1809	15.7	16.0	16.4	143.0	205.3	255.3	15.7	15.8	15.9	228.1	248.9	269.3
1810	15.1	15.6	16.0	234.1	281.5	333.8	15.9	16.1	16.4	240.9	265.1	289.3
1811	15.8	16.1	16.4	189.9	221.1	283.4	15.6	15.8	16.0	199.1	213.5	226.1
1812	15.5	15.8	16.4	207.4	262.7	302.8	15.9	16.0	16.2	242.2	257.6	267.0
1813	16.0	16.4	16.8	243.7	286.3	319.7	15.9	16.0	16.1	231.5	242.0	250.3
1814	16.2	16.5	16.8	187.5	217.1	251.1	15.6	15.7	15.8	226.3	235.5	245.7
1815	15.2	15.6	16.0	174.4	210.4	251.9	15.6	15.7	15.8	208.0	218.3	231.2
1816	15.6	16.1	16.3	190.3	234.2	282.2	16.0	16.1	16.1	235.1	246.1	259.2
1817	16.3	16.7	16.9	220.1	250.9	292.4	16.0	16.1	16.2	228.6	240.0	252.4
1818	15.0	15.3	15.6	173.0	197.9	219.8	15.5	15.7	15.8	201.4	213.4	225.9
1819	15.1	15.7	16.0	213.2	257.4	334.5	15.9	16.0	16.2	236.5	252.7	271.7
1820	16.2	16.6	17.0	231.6	284.3	331.0	15.9	16.1	16.3	237.1	262.0	283.1
1821	15.2	15.6	15.9	185.7	229.4	277.8	15.5	15.7	15.9	214.1	225.7	240.3
1822	15.5	16.0	16.4	194.1	243.4	297.1	15.9	16.0	16.2	245.8	262.1	277.2
1823	16.2	16.6	16.8	159.7	200.6	230.1	15.6	15.7	15.8	213.3	221.6	231.5
1824	14.6	15.2	15.5	201.0	248.4	308.3	15.7	15.8	15.8	223.8	229.6	237.6
1825	15.6	15.9	16.2	204.6	256.5	303.0	15.1	15.3	15.5	159.0	176.4	201.3
1826	16.3	16.8	17.1	194.5	237.8	278.7	16.2	16.3	16.5	250.8	271.9	291.5
1827	15.0	15.3	15.7	127.7	175.1	211.2	15.1	15.3	15.6	135.0	155.1	179.8
1828	14.7	15.1	15.5	150.1	201.9	270.1	15.6	15.8	16.0	204.0	226.4	248.7
1829	15.6	16.0	16.3	203.2	251.3	303.7	15.8	16.0	16.1	183.0	205.8	229.7
1830	16.5	16.9	17.3	234.9	277.1	315.0	16.7	17.0	17.2	275.4	321.1	354.9
1831	15.0	15.4	15.8	186.5	238.2	286.4	15.3	15.7	16.1	180.7	204.9	237.0
1832	15.6	16.0	16.5	210.4	267.7	301.5	15.6	15.9	16.3	253.3	285.2	312.7
1833	15.9	16.2	16.5	238.2	268.0	319.5	16.3	16.5	16.6	268.2	292.8	310.0
1834	15.0	15.2	15.6	207.1	247.0	288.2	15.7	15.9	16.1	226.3	249.7	268.0
1835	16.1	16.4	16.7	182.5	241.6	303.5	15.5	15.8	15.9	217.5	238.8	259.8
1836	15.6	15.8	16.2	156.5	193.9	224.0	15.7	15.9	16.0	211.4	223.6	240.8
1837	15.3	15.6	15.9	220.2	243.9	275.5	15.8	15.9	16.1	215.7	234.3	253.0
1838	15.9	16.2	16.6	132.0	194.3	241.6	15.7	15.8	15.9	211.5	218.4	230.2

Year	GRAT 90%L	GRAT	GRAT 90%U	GRAP 90%L	GRAP	GRAP 90%U	THRT 90%L	THRT	THRT 90%U	THRP 90%L	THRP	THRP 90%U
1839	15.0	15.6	15.9	200.7	237.2	281.2	15.9	15.9	16.0	227.6	234.5	246.2
1840	16.4	16.7	16.9	222.4	245.1	276.5	16.2	16.3	16.4	253.0	263.9	277.6
1841	15.1	15.4	15.9	141.2	179.4	209.9	15.1	15.2	15.5	154.8	169.3	187.2
1842	15.9	16.4	16.7	210.6	258.5	299.9	15.7	15.9	16.2	207.2	232.9	256.8
1843	15.1	15.6	15.9	167.1	222.2	270.0	15.9	16.1	16.3	209.3	227.5	241.1
1844	15.9	16.2	16.5	231.2	275.4	307.2	16.0	16.2	16.3	258.2	270.8	280.0
1845	14.7	15.0	15.3	120.6	164.9	204.1	15.4	15.5	15.6	197.7	214.9	228.5
1846	14.5	15.0	15.4	247.0	289.5	334.8	16.2	16.4	16.6	292.8	307.1	319.6
1847	16.3	16.7	17.2	239.6	300.5	326.7	16.1	16.4	16.6	254.0	285.8	311.2
1848	14.8	15.2	15.5	148.6	196.9	261.7	15.2	15.4	15.6	197.5	235.1	269.9
1849	15.9	16.3	16.6	246.4	286.7	341.8	15.8	16.0	16.2	281.5	294.2	317.6
1850	15.1	15.4	15.8	124.2	166.2	210.6	15.8	15.9	16.1	228.5	241.3	250.0
1851	15.3	15.6	15.9	179.7	209.0	247.6	15.6	15.7	15.7	221.9	237.5	251.9
1852	15.4	15.8	16.2	261.4	293.8	345.3	15.6	15.7	15.8	222.0	229.1	238.3
1853	15.2	15.7	16.4	169.9	219.9	274.6	15.7	15.8	15.9	208.3	219.2	236.3
1854	16.2	16.6	16.8	251.8	293.3	319.9	16.1	16.3	16.5	244.1	261.2	279.4
1855	16.0	16.3	16.8	207.9	237.6	291.1	15.7	15.9	16.0	186.0	209.5	232.6
1856	15.0	15.3	15.6	226.6	263.5	290.1	15.5	15.7	15.9	206.6	223.1	240.9
1857	15.1	15.4	15.8	220.5	278.7	325.3	15.8	15.8	15.9	228.1	232.8	240.9
1858	15.4	15.6	16.1	216.3	269.7	311.3	16.1	16.1	16.2	249.6	261.7	270.0
1859	15.7	16.1	16.4	162.8	214.0	254.3	15.6	15.7	15.8	209.9	225.7	239.0
1860	15.4	15.8	16.2	244.4	275.8	330.4	16.0	16.1	16.2	268.3	275.8	283.3
1861	14.2	14.8	15.2	15.0	91.3	149.7	15.0	15.2	15.4	141.5	157.1	180.2
1862	16.0	16.3	16.6	159.4	212.6	271.8	15.4	15.6	15.9	184.8	207.6	238.8
1863	15.0	15.4	16.0	164.8	233.8	282.8	15.3	15.5	15.8	141.0	163.6	196.1
1864	15.3	15.5	15.9	147.9	197.9	238.5	15.6	15.7	15.9	203.3	219.2	243.1
1865	16.4	16.7	16.9	260.0	304.1	336.1	16.3	16.5	16.8	276.3	295.9	320.7
1866	14.3	14.8	15.2	109.0	166.1	240.9	14.9	15.1	15.4	154.5	190.5	229.3
1867	16.2	16.7	17.1	200.7	265.2	312.2	16.0	16.2	16.6	267.0	291.0	315.8
1868	15.3	15.5	15.9	146.2	191.5	228.2	15.4	15.7	15.9	185.4	205.5	237.9
1869	15.2	15.4	15.7	153.9	222.5	273.0	15.6	15.8	16.0	232.5	253.5	276.5
1870	16.0	16.2	16.5	235.1	262.0	300.7	15.8	15.9	16.0	230.5	240.4	248.2
1871	15.4	15.7	16.2	172.8	208.5	239.9	15.8	15.8	15.9	223.8	227.5	232.4
1872	15.6	16.0	16.4	292.9	328.7	387.1	16.6	16.9	17.1	299.5	326.8	353.2
1873	15.6	16.0	16.3	166.2	217.4	271.9	15.2	15.4	15.8	159.7	202.2	241.7
1874	14.9	15.3	15.6	203.4	240.4	280.9	15.2	15.5	15.7	227.6	263.3	296.0
1875	15.2	15.6	16.0	228.5	289.2	335.1	15.4	15.7	15.9	211.3	233.5	250.5
1876	15.2	15.5	15.8	173.6	207.4	234.9	15.2	15.5	15.7	193.1	217.8	244.4
1877	15.2	15.4	15.8	177.8	213.8	252.2	15.5	15.8	16.1	237.3	260.6	281.7
1878	15.3	15.7	16.1	193.2	235.9	296.5	15.8	16.2	16.6	250.2	269.4	296.7
1879	15.6	15.8	16.1	180.3	209.0	230.9	15.6	15.8	16.0	191.5	218.0	239.0
1880	15.9	16.1	16.4	164.9	213.4	261.2	15.8	16.0	16.2	220.7	235.7	251.8
1881	15.7	16.0	16.3	199.1	233.9	258.5	15.7	15.9	16.0	210.8	224.3	237.6
1882	15.5	15.8	16.2	219.1	287.8	349.5	15.9	16.1	16.2	240.6	254.9	265.9
1883	16.4	16.8	17.3	251.9	292.2	350.7	16.2	16.4	16.5	268.5	292.0	304.8
1884	15.2	15.6	16.3	167.5	237.0	295.4	15.8	16.0	16.2	227.5	250.4	263.1
1885	15.0	15.3	15.6	192.7	222.1	259.6	15.4	15.6	15.9	207.7	231.8	248.8
1886	15.4	15.9	16.2	241.1	275.6	315.5	15.8	16.0	16.2	248.2	266.6	285.1
1887	16.0	16.5	16.8	246.3	285.8	348.2	15.6	15.7	15.9	221.8	240.7	257.7
1888	15.1	15.4	15.9	217.5	261.9	327.9	15.9	16.0	16.2	248.0	262.7	277.8
1889	15.7	15.9	16.3	182.0	217.6	267.0	15.6	15.7	15.8	215.1	221.1	229.8
1890	15.5	16.0	16.4	145.0	190.9	223.6	15.5	15.6	15.7	197.8	210.1	225.7
1891	15.3	15.6	15.9	199.9	235.2	275.7	15.7	15.8	15.9	198.7	210.1	228.8
1892	15.2	15.6	16.0	199.6	233.4	266.0	15.7	15.8	16.0	206.6	220.0	234.3
1893	15.3	15.6	15.9	222.4	255.9	284.8	15.8	15.9	16.0	214.9	227.4	238.8
1894	16.1	16.4	16.7	173.7	208.8	250.4	15.9	15.9	16.0	216.9	225.6	231.5
1895	16.2	16.5	16.9	214.7	262.6	297.2	15.9	16.0	16.1	243.7	258.2	269.3
1896	14.2	14.5	14.9	101.2	145.7	193.8	14.8	15.1	15.3	151.2	192.1	227.1
1897	15.6	15.9	16.3	183.1	222.8	257.6	15.5	15.9	16.1	236.5	262.1	285.6
1898	15.0	15.6	16.3	179.3	215.6	276.1	15.1	15.5	15.8	129.6	164.6	201.5
1899	15.2	15.7	15.9	137.8	167.9	220.8	15.2	15.5	15.7	137.4	170.2	198.8
1900	15.6	15.9	16.3	154.7	182.5	237.7	15.3	15.6	15.8	149.9	171.3	202.3
1901	15.2	15.7	16.2	121.8	175.2	211.3	15.5	15.8	16.0	168.4	192.6	216.3
1902	15.6	16.0	16.3	209.6	270.5	315.1	16.3	16.5	16.6	235.3	261.1	291.6
1903	15.3	15.6	16.0	167.1	193.3	217.5	15.7	15.9	16.1	207.7	222.3	234.2
1904	15.8	16.3	16.6	294.6	332.7	367.4	16.3	16.5	16.7	279.7	307.1	325.0
1905	16.0	16.3	16.6	205.2	232.6	276.9	15.4	15.6	15.9	201.4	222.0	244.6
1906	15.4	15.7	16.1	237.4	269.4	294.4	15.5	15.7	15.9	234.9	258.4	276.1
1907	15.9	16.2	16.6	285.8	317.3	356.5	16.5	16.8	17.1	297.3	330.1	355.3
1908	14.7	15.0	15.3	168.8	225.7	262.8	15.4	15.7	15.9	193.2	224.3	251.5
1909	15.7	16.1	16.4	222.4	256.7	284.8	15.2	15.6	15.8	208.7	237.0	261.3
1910	16.5	16.8	17.0	229.5	270.5	313.3	16.4	16.5	16.7	265.5	293.1	311.6
1911	15.2	15.4	15.8	196.0	231.7	249.3	15.6	15.8	16.0	196.1	212.8	229.1
1912	15.4	15.8	16.3	260.1	280.3	306.9	15.9	16.1	16.4	252.2	277.4	297.6
1913	15.7	15.9	16.2	163.9	192.0	222.0	15.6	15.7	15.8	209.8	224.1	233.8
1914	15.1	15.4	15.8	170.0	208.5	248.3	15.4	15.6	15.7	203.5	221.4	241.6
1915	15.1	15.5	15.8	163.4	206.8	252.5	15.3	15.5	15.6	182.4	209.1	241.5
1916	17.1	17.4	17.9	267.6	305.4	351.3	16.4	16.8	17.1	288.1	318.2	351.0
1917	15.0	15.4	15.9	132.3	183.7	219.1	14.8	15.0	15.3	112.4	144.9	172.0
1918	16.1	16.5	16.8	250.4	302.0	346.9	16.1	16.3	16.6	280.7	308.9	336.5
1919	14.8	15.2	15.7	160.9	198.3	239.8	15.3	15.6	15.8	146.4	171.1	196.5

Year	GRAT 90%L	GRAT	GRAT 90%U	GRAP 90%L	GRAP	GRAP 90%U	THRT 90%L	THRT	THRT 90%U	THRP 90%L	THRP	THRP 90%U
1920	15.9	16.2	16.4	264.9	293.2	319.1	16.0	16.1	16.2	269.8	282.0	297.1
1921	14.8	15.1	15.4	129.8	168.1	214.7	15.2	15.3	15.5	153.8	167.3	183.4
1922	15.2	15.4	15.7	196.6	235.8	281.7	15.7	15.9	16.1	236.2	250.7	271.2
1923	15.2	15.7	16.3	182.8	225.2	265.3	15.8	16.0	16.3	205.1	226.0	249.7
1924	16.5	16.8	17.1	264.4	293.9	335.3	16.5	16.7	16.9	275.2	301.8	324.3
1925	15.7	16.1	16.7	200.7	246.2	298.4	15.8	16.0	16.3	219.3	250.0	271.3
1926	15.0	15.3	15.6	169.4	201.8	262.6	15.0	15.4	15.7	180.8	213.7	242.6
1927	15.9	16.2	16.4	240.9	274.4	311.5	16.0	16.1	16.3	253.6	269.4	289.5
1928	16.3	16.6	16.8	209.9	252.9	286.2	15.8	16.1	16.3	209.3	237.8	265.7
1929	15.9	16.2	16.6	208.1	245.7	279.7	15.6	15.9	16.2	215.4	243.9	273.8
1930	15.6	16.0	16.2	264.1	300.4	343.6	16.0	16.3	16.5	263.2	296.7	326.4
1931	14.8	15.0	15.3	173.8	191.7	227.8	15.2	15.4	15.6	185.9	213.2	229.8
1932	15.0	15.3	15.7	153.0	200.8	240.2	15.1	15.3	15.5	178.7	209.5	237.8
1933	15.1	15.6	16.3	93.8	145.3	205.2	15.5	15.7	16.0	186.4	209.1	237.8
1934	15.1	15.5	15.9	159.5	199.1	265.7	15.6	15.9	16.1	188.3	211.7	244.9
1935	16.6	17.3	17.7	320.7	369.2	432.6	16.6	17.1	17.4	307.6	346.0	387.9
1936	14.5	14.9	15.6	152.2	195.3	227.6	15.4	15.7	16.1	166.8	216.9	245.3
1937	14.7	15.2	15.6	165.4	215.1	266.1	15.0	15.4	15.8	199.6	246.4	285.8
1938	16.3	16.8	17.1	263.0	304.1	353.6	16.3	16.5	16.7	284.7	298.1	318.1
1939	15.7	15.9	16.3	223.6	258.8	299.6	16.1	16.4	16.7	228.6	266.4	295.2
1940	14.6	14.9	15.6	182.1	227.3	299.2	15.4	15.7	16.2	205.2	232.9	263.4
1941	14.9	15.3	15.8	235.0	265.8	313.9	15.6	15.8	16.0	227.7	247.2	261.6
1942	14.6	15.0	15.3	202.3	243.2	286.1	15.6	15.7	15.9	207.8	221.4	232.6
1943	15.1	15.5	15.9	146.4	184.0	236.0	15.3	15.6	15.8	198.7	237.5	267.7
1944	15.8	16.1	16.4	211.4	245.4	280.9	15.5	15.8	16.0	233.8	251.1	269.5
1945	15.5	15.9	16.3	194.6	236.8	272.7	15.8	16.0	16.3	237.3	262.5	284.1
1946	15.3	15.9	16.3	247.5	290.2	317.9	15.9	16.1	16.2	243.2	256.6	266.7
1947	15.7	16.3	16.6	116.8	166.4	215.6	15.4	15.6	15.7	198.2	211.1	227.2
1948	15.6	15.9	16.2	269.3	317.7	349.0	15.9	16.0	16.1	233.8	246.0	259.1
1949	14.6	15.0	15.3	168.3	206.7	254.6	15.7	15.9	16.1	193.5	214.6	231.5
1950	14.8	15.0	15.3	173.6	205.7	250.3	15.3	15.5	15.7	174.2	197.8	222.2
1951	15.9	16.3	16.7	209.2	242.5	293.0	15.6	15.8	16.0	203.0	224.0	245.6
1952	15.6	16.0	16.5	164.0	203.1	253.6	15.7	16.0	16.3	176.1	201.6	233.4
1953	15.8	16.1	16.4	189.2	215.9	252.2	15.8	15.9	16.1	211.6	224.7	236.6
1954	15.2	15.8	16.2	237.2	285.5	313.1	16.1	16.2	16.4	256.7	272.1	281.7
1955	15.9	16.5	16.9	206.0	244.2	312.3	15.7	15.9	16.0	230.7	246.2	258.0
1956	15.9	16.2	16.4	215.7	251.0	274.8	15.8	15.9	16.1	244.5	259.7	272.3
1957	15.8	16.2	16.5	191.5	219.8	257.2	15.7	15.8	15.8	217.0	222.3	228.4
1958	16.2	16.6	16.9	184.2	216.5	269.6	15.6	15.8	15.9	197.3	209.9	222.7
1959	16.1	16.5	16.7	219.0	265.4	308.5	15.7	15.9	16.0	196.7	209.3	221.2
1960	15.3	15.7	16.4	172.9	218.1	287.9	15.5	15.7	15.8	187.7	201.7	214.3
1961	15.5	15.8	16.2	253.7	307.3	347.8	16.0	16.1	16.2	221.6	241.5	254.0
1962	16.3	16.6	17.0	251.0	327.1	378.2	15.9	16.1	16.2	221.5	242.2	259.6
1963	15.4	15.8	16.3	101.4	146.8	185.3	15.2	15.4	15.7	170.2	182.0	200.1
1964	15.1	15.5	15.8	202.2	243.0	301.7	15.7	15.9	16.2	200.9	236.9	284.4
1965	15.1	15.5	15.8	156.3	195.4	245.2	15.8	16.1	16.4	174.1	210.2	253.1
1966	16.2	16.5	16.9	187.7	230.2	261.6	15.9	16.3	16.6	224.8	262.9	292.3
1967	15.1	15.4	15.7	144.1	184.4	213.2	15.4	15.7	15.9	207.5	236.7	261.3
1968	16.2	16.6	16.8	265.8	294.9	327.0	15.9	16.2	16.4	277.2	294.1	311.9
1969	15.9	16.2	16.4	153.6	189.1	220.3	15.5	15.7	15.9	209.1	230.6	248.5
1970	15.7	16.0	16.4	237.3	264.8	291.7	16.0	16.1	16.4	250.5	274.2	292.6
1971	16.1	16.3	16.6	202.2	224.9	246.4	15.8	15.9	16.1	215.2	225.1	236.8
1972	15.7	16.1	16.6	212.9	278.1	327.5	15.7	15.9	16.2	236.5	255.5	276.4
1973	15.5	16.0	16.5	137.0	194.7	242.8	15.7	15.8	15.9	219.7	228.3	239.1
1974	15.9	16.3	16.6	209.0	237.3	271.6	15.7	16.0	16.2	194.3	216.0	246.8
1975	16.4	16.6	16.9	182.6	231.5	271.4	15.7	16.0	16.2	181.3	212.9	241.9
1976	14.8	15.2	15.6	200.5	233.4	272.5	15.5	15.7	16.0	183.3	202.8	231.0
1977	15.9	16.1	16.4	244.5	275.7	310.6	15.5	16.0	16.3	214.3	253.3	304.0
1978	16.0	16.3	16.7	214.8	253.4	294.1	15.8	16.1	16.6	261.8	301.5	338.8
1979	15.4	15.7	16.0	222.2	263.4	297.3	15.4	15.7	16.0	226.8	276.7	315.5
1980	14.8	15.2	15.7	199.5	235.2	298.7	15.4	15.7	16.0	259.9	284.9	307.6
1981	16.1	16.6	17.3	250.0	284.6	336.4	16.0	16.3	16.6	253.0	284.4	314.2
1982	15.6	15.9	16.2	150.5	197.3	216.8	15.5	15.7	15.9	183.0	202.0	216.7
1983	15.4	15.9	16.1	206.1	236.1	267.3	15.1	15.4	15.6	185.0	211.1	241.6
1984	15.8	16.5	16.8	236.0	280.5	340.7	15.7	16.0	16.2	247.8	260.3	276.7
1985	15.8	16.3	16.8	114.4	175.6	238.8	15.6	15.9	16.1	189.0	217.1	248.9
1986	15.6	15.9	16.3	172.9	212.9	241.0	15.9	16.1	16.3	228.9	242.3	257.8
1987	14.5	14.8	15.1	174.1	227.5	284.6	14.6	15.1	15.5	124.8	186.9	247.5
1988	.	.	.	.	.	.	15.9	16.4	16.9	323.2	344.4	370.3
1989	.	.	.	.	.	.	14.9	15.4	16.0	119.3	175.4	240.9
1990	.	.	.	.	.	.	15.9	16.3	16.6	222.2	260.0	288.9